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HYDROTHERMAL ALTERATION OF IGNEOUS ROCKS

BY GEORGE M. SCHWARTZ

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ABSTRACT

Many studies of individual examples of hydrothermal alteration have been made, but a general summary has not appeared since 1915. The changes due to hydrothermal alteration are textural, mineralogical, and chemical.

As a rule the primary texture is destroyed, roughly in proportion to the intensity of alteration, but only in extreme examples is it entirely gone. Many of the rocks are softened and bleached and consist of a felt-like or messy aggregate of secondary minerals. Less commonly the rock remains fresh, owing to the development of anhydrous minerals such as albite.

The most common secondary minerals, approximately in order of abundance, are: sericite, quartz, pyrite, carbonates, chlorite, epidote, alunite, adularia, albite, various sulphides and numerous less common, but at places characteristic, minerals.

Chemical changes are extensive and vary widely. An average has been made of all available pairs of analyses divided into acid, intermediate, and basic types, as well as a combined average. Comparison of altered with fresh rock shows a gain in potassa and water, a loss in iron, magnesia, lime, and soda, and little change in silica and alumina during alteration.

Diagrams are used to bring out significant features of various groups of analyses as well as of the averages prepared.

INTRODUCTION

Important studies of hydrothermal alteration of igneous rocks have been published in increasing numbers in the last two decades. No attempt seems to have been made to summarize these results, at least from the chemical point of view, since the publication of Leith and Mead's *Metamorphic geology* in 1915. The most important generalizations have appeared in the successive editions of Lindgren's *Mineral deposits,* but the treatment is related to the various types of mineral veins rather than to the alteration of igneous rocks as a group. It seems desirable, therefore, to bring together, insofar as practicable, the data published during the past 40 years of active work, particularly in America. The data summarized here are believed to be typical and an effort has been made to avoid generalizations not supported by good evidence. It would no doubt be helpful to include a tabulation of all of the analyses utilized, but the desire to limit the paper to a reasonable length led to their exclusion. The references are cited at the end of the paper, and those containing the analyses here used are designated by an asterisk.

Since the paper was completed, three pairs of analyses have been published by Callaghan and Buddington (1938, p. 32).

Really significant chemical and mineralogical studies of the hydrothermal alteration of igneous rocks were first made by Lindgren (1894, p. 274-278; 1897, p. 638-647; 1899, p. 174-187, 218-231) in his reports on mineral deposits in California and Idaho. These reports were followed by his paper on metasomatic processes in fissure veins (Lindgren, 1901, p. 578-692) which is unquestionably one of the most important studies of wall-rock alteration. It seems to be the first generalized treatment of the subject with the use of numerous analyses of fresh and altered rocks and is based largely on Lindgren's own data.

The history of the development of the early ideas on metasomatic replacement in wall rocks is reviewed by Lindgren (1901), and this historical aspect is not repeated here. The problem of calculation of changes is also treated critically by Lindgren with the correct procedure outlined.

Hydrothermal alteration or metamorphism has been used in varying senses, and the recent tendency seems to be to embrace all changes after the first crystallization in an igneous rock, thus including deuteric, pneumatolytic, and allied processes. This does not seem to be the sense in which the term was originally used.

Hydrothermal alteration of igneous rocks as used in this paper refers to the changes the rock has undergone after consolidation through the agency of hot solutions and subordinate gases. In some cases the solutions may have been derived from other and deeper portions of the same igneous mass, but often they originate from later igneous rocks.

Changes during the late stages of crystallization of the rock itself are not included, and contact metamorphism is also excluded. Lindgren defines hydrothermal metamorphism simply as including the changes effected in rocks by hot ascending waters.

Estimates of the temperature of hydrothermal alteration are difficult to make, but it probably takes place almost entirely below 500° C., and the most characteristic processes discussed here may actually go on mainly at or below 300° C.

The writer is indebted to Mr. C. C. Allen, who assisted greatly in the tedious work of tabulation and calculation of chemical data. A grant from the research funds of the Graduate School of the University of Minnesota made possible the employment of Mr. Allen, and this aid is gratefully acknowledged. Many suggestions were kindly offered by Professors W. H. Emmons and F. F. Grout.

It is evident from the mode of treatment that the writer has adopted methods from the work of Leith and Mead under whom the writer had the privilege of studying metamorphic geology. It is a pleasure to

acknowledge the value of their methods as well as their stimulation of interest in the problem.

PHYSICAL CHANGES

The most common change brought about by hydrothermal alteration, especially at shallow depths, is the softening and bleaching of the original igneous rocks. The acidic rocks become white and chalklike. The more basic rocks become grayish green and even white. Sericitization particularly results in softening and bleaching. A few examples serve to illustrate the changes.

Lindgren (1894, p. 243) described amphibolite at Ophir, California, which altered to a grayish or white, fine-grained rock with greasy luster. Granodiorite in the same area altered to a grayish-green rock.

In the Idaho basin Lindgren (1897, p. 178) found basalt at advanced stages of alteration changed to a bluish-green or yellowish-green rock. In extreme cases basalt and rhyolite were difficult to distinguish. A dioritic granite likewise altered to a soft white rock with seams of sulphide.

In silicic rocks the ferromagnesian minerals seem characteristically to have altered early and disappeared, resulting in a marked bleaching. Pyrite may replace many primary ferromagnesian minerals, but quartz, sericite, carbonate, and alunite also replaced them.

Weed (1912, p. 87) described the Butte quartz monzonite as transformed from a hard dark rock to a soft bleached dull white or gray clay-like or talcy mass. Kirk (1912, p. 52) emphasized that the sericitized rock at Butte has a dull luster and an extremely fine dense felt-like mass difficult to analyze under the microscope.

The rocks in the Cripple Creek district (Lindgren and Ransome, 1906, p. 184) furnish excellent examples of alteration. Hard bluish-gray breccia has locally changed to a greenish-gray rock with the replacement of the dark silicates by sericite, carbonate, and pyrite. Basic dikes have altered to soft greenish-gray sheets. Reddish granite bleached to a light gray.

In the San Juan region of Colorado (Cross and Larsen, 1935, p. 12) large bodies of volcanic rock have been altered to a light-gray, white, or iron-stained earthy material made up largely of kaolinite or sericite or alunite, quartz, and pyrite.

At Goldfield (Ransome *et al.*, 1909, p. 182) the igneous rocks are altered to a soft light-colored mass of quartz, kaolinite, alunite, and pyrite. The original texture is largely obliterated.

McCann (1922, p. 359) has described a dark-gray augite diorite in the Bridge River district which bleached to a whitish-gray soft rock.

Butler and Burbank (1929, p. 108) state that the most pronounced effect of alteration in the Michigan copper districts is the bleaching of the basic flows.

At Tonopah, Nevada, nearly black andesite altered to a gray with dull white altered feldspar phenocrysts.

The Bingham quartz monzonite was changed by hydrothermal alteration to a dull, light colored, slightly porous rock with veinlets of carbonate, sulphides, and other minerals.

MacDonald (1909, p. 82) describes the alteration of andesite in the Bohemia district of Oregon as follows:

> "In the vicinity of the veins the mineralizing solutions have greatly altered the country rock. Several hundred feet distant from a vein the dark color of the rock is in many places changed to a greenish tinge, while close to the deposit it is grey to buff in color, has a clayey appearance and crumbles easily. The pattern of the rock is fairly well preserved, however, the outlines of the feldspar phenocrysts being clearly visible, though the feldspar material has been changed to a white or yellowish powder."

Primary textures persist through a great deal of alteration, but in the most intensely affected rocks practically no trace may remain. In coarse-grained rock quartz frequently retains its form after other minerals have been replaced by fine-grained aggregates. Veinlets are common, as are small vugs more or less filled with crystals of secondary minerals. In some districts the alteration took place in definite stages. Spencer (1917, p. 55) recognized three stages in the alteration of porphyry at Ely, Nevada: (1) permeation of the rock by solutions capable of producing alterations; (2) formation of veinlets, usually of quartz or quartz with a little orthoclase and biotite carrying distributed pyrite and chalcopyrite; (3) the deposition of pyrite films in fractures.

Butte shows three stages or zones of alteration, although analyses for only the first two have been published. The sequence which appears to be a common one is silicification in the immediate wall rock of the veins, grading to a zone of sericitization with propylitization still farther out.

Tintic (Lindgren and Loughlin, 1919, p. 98) has similar zones in monzonite and latite. Close to the veins the rocks have been completely replaced by quartz and pyrite with very little sericite. The margins of these veins pass gradually into a quartz-sericite-pyrite rock which preserves the original texture of the igneous rocks. As distance from the vein increases this rock passes into a green or greenish-gray rock, in which chlorite and epidote are present as well as sericite and calcite and a little pyrite.

Where silicification took place the rock naturally is hard and dense and frequently forms a chalcedonic or jasperoid type. Such zones are

often expressed at the surface as irregular knobs or craggy points or ridges and are locally referred to as quartzite dikes, iron dikes, or other more or less appropriate terms. Schrader (1923, p. 35) described rhyolite which has been devitrified and silicified and left apparently fresh and unaltered. In the deeper zones under more intense conditions the rocks remain fresh in appearance owing to the development of anhydrous silicates such as albite.

Nolan (1935, p. 53) has described the alteration of volcanic necks in the Gold Hill district, Utah. Tridymite, opal, chalcedony, quartz, and calcite, evidently formed in the order named, and found in veinlets.

At Tonopah (Spurr, 1905, p. 207) the andesite is altered to a siliceous light-colored rhyolitic appearance.

In the Bonanza district, Burbank (1932, p. 73) describes red or brown "jaspers" which are the product of replacement of andesitic rocks.

A review of several descriptions indicates that many changes may be seen under the microscope which are not conspicuous in hand specimen. Faint traces of the original texture may remain in a fine aggregate of sericite, quartz, and carbonate. Accessory minerals of the original rock may remain essentially unaltered and be a guide to the original character of the rock. Apatite and less commonly zircon are particularly useful in this respect.

As a result of the prevalence of pyrite in hydrothermally altered rocks they are particularly susceptible to attack by weathering so that rocks which have been bleached are stained brown, yellow, and red and may be further softened. Box-work is likely to develop because of the presence of narrow resistant quartz veinlets.

The textural changes may be generalized somewhat as follows: original granitic, porphyritic, diabasic, or other textures are gradually destroyed; pseudomorphism is common in the early stages, but the pseudomorphs may ultimately disappear; in the most advanced stages there remains a felted mass or irregular aggregate, and evidence of the original character may be difficult to find, particularly in hand specimen.

VOLUME CHANGES

Possible changes in volume are of great importance in considering the significance of chemical changes as indicated by chemical analyses of fresh and altered rock. Lindgren (1918, p. 542-554) has discussed this problem in some detail.

In general there is little evidence of any appreciable swelling or contraction of the rock mass as a whole during hydrothermal alteration of igneous rocks. Frequently sufficient primary texture is preserved to disprove any considerable volume change. The principal change

then in absolute amount of material added or removed may be estimated by considering the bulk specific gravity of the fresh and altered rocks. Unfortunately this important information has frequently been omitted from the analyses.

In the districts described in the literature a decrease in lump specific gravity has usually resulted from hydrothermal alteration. This is mainly due to the development of porosity and of hydrous minerals of low specific gravity. There are, however, exceptions where important amounts of sulphide are formed or where introduction is particularly important. Specific gravity may be increased and porosity reduced by vein solutions, as pointed out by Ransome (1911, p. 97) for the diorite porphyry at Breckenridge, Colorado.

Several writers emphasize that some specific reactions of hydrothermal alteration call for relatively large increases in volume, provided the change involved substitution of molecule for molecule. Positive evidence of lack of volume change in some examples of this sort—pseudomorphism for instance—suggests that only such material remains as is necessary for the new minerals.

The most important changes in absolute amounts are due to the development of porosity and the change in specific gravity of minerals. An example of changes in the specific gravity of rocks is shown in the San Francisco district, Utah (Butler, 1913, p. 76), where fresh quartz monzonite in the Cactus mine has a density of 2.72, whereas the altered rock density is 2.52. In the O.K. mine the densities are 2.64 and 2.27 respectively for fresh and altered rock. Other examples are furnished by granite at Climax, Colorado, with densities of 2.52 and 2.23. The Bonanza district, Colorado, shows both increase and decrease during alteration. Fresh andesite has a density of 2.71, silicified andesite with hematite a density of 3.07, and silicified andesite 2.59.

Allen and Day (1935, p. 132) found comparatively little volume change in the rocks near the hot springs of Yellowstone Park. They state:

> "So far as the rock that has been partially exposed by drilling is concerned, more material by weight is constantly added than is being removed by hot water, and the volume of the rock cannot change more than a small percentage in either direction."

MINERAL ALTERATIONS

GENERAL STATEMENT

The detailed changes in rocks are commonly described in terms of mineralogical changes which can be recognized by examination of hand specimens or by microscopic and chemical studies. Most descriptions are based on the study of hand specimens and thin sections, but most

quantitative data are available through calculations of mineral compositions from chemical analyses. Particularly valuable in this respect are papers by Lindgren (1901; 1905), Ransome (1901; 1911), Knopf (1913), Butler (1913), Spencer (1917), and Butler and Vanderwilt (1933).

The quantitative mineral data reported in this paper have been computed by the original investigators. The writer planned to compute additional mineral compositions from the available chemical data, but the danger of introducing errors where an intimate knowledge of the district was lacking made this inadvisable. It is nevertheless true that some special cases would doubtless give significant data by calculation.

It is common practice to discuss the mineral changes under the heading of some process, and this custom is followed here. Discussion of the processes separately does not mean that they are usually distinct. In many cases, two or more alterations go on simultaneously, or one process follows another with considerable overlapping. Cerro de Pasco offers a particularly good example of successive phases (Graton and Bowditch, 1936).

A review of all the examples of alteration for which pairs of analyses are available showed that more than half of them represent a combination to an important degree of two or more processes. Extreme examples where one process greatly predominates are cited at several places in this paper. Districts which show good examples of combined processes include Rio Tinto, Spain, where sericitization is followed by carbonation, chloritization, and propylitization. At Bonanza, Colorado, silicification, sericitization, carbonation, and chloritization of andesite is seen, but extreme silicification at places excludes the others. At Cripple Creek the rocks show a combination of sericitization, carbonation, and development of adularia. Carbonation and sericitization were important in the wall-rock alteration of several California districts as well as in various scattered districts. At Goldfield, Nevada, dacite has been effected by a combination of kaolinization, alunitization, and pyritization. Deposits at Bayard, New Mexico, show sericitization, epidotization, and chloritization. Many other examples might be cited.

SILICIFICATION

Silicification is common but by no means universal in hydrothermal alteration of igneous rocks; actual desilication sometimes takes place. This is shown especially by the replacement of quartz by sericite. One of the most striking examples of silicification is that of the Climax molybdenum deposit which has recently been described in some detail by Butler and Vanderwilt (1933, p. 195). This deposit is roughly conical with concentric zones of varying intensity of mineralization of

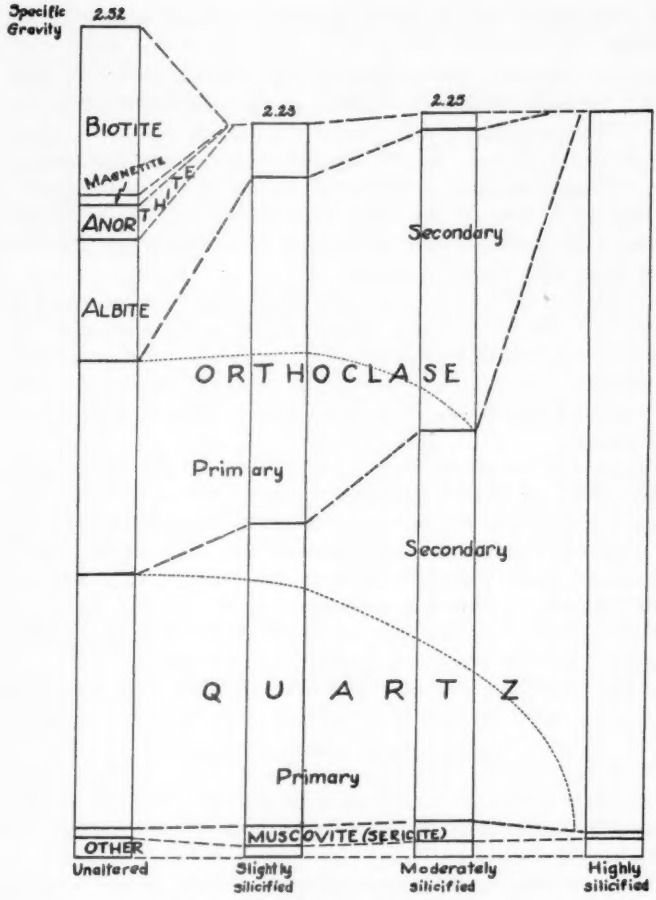

FIGURE 1.—*Mineral changes in alteration of granite*
Climax, Colorado. (After Butler and Vanderwilt, 1933, p. 224)

granite. The outer zone is lightly silicified, the next zone with molybdenite is moderately silicified, and the inner core is highly silicified. Calculated mineral composition based on chemical analyses and thin-section measurements shows 31.63 per cent quartz in the original granite, 49.50 per cent in the ore zone, and 98 per cent in the core (Fig. 1).

At De Lamar, Idaho (Lindgren, 1899, p. 178), rhyolite is highly silicified near the veins with the preservation of the original structure of

the rock. Calculation of mineral composition indicates nearly 80 per cent quartz.

At Tonopah, Nevada (Spurr 1904, p. 207), silicification has been important. Andesite altered to a siliceous, light-colored rhyolitic appearance. The microlitic, nearly glassy groundmass has been largely decomposed to, or replaced by, fine granular quartz with fine muscovite. In advanced stages of alteration the entire mass forms a quartz-sericite aggregate. The quartz varies from microcrystalline to moderately coarse. In extreme stages the quantity of sericite is less and that of quartz more than in early stages.

Beeson (1913, p. 356) notes that in the early hydrothermal period at Bingham, Utah, the feldspar groundmass of the quartz monzonite was almost completely replaced by fine-grained secondary quartz, and feldspar phenocrysts are partly or completely replaced by quartz. The writer recently examined rock from Maguarichic, Mexico, which showed the same changes.

Silicification and sericitization frequently seem to take place simultaneously. Thus, at Miami, Ransome (1919, p. 160) states that silicification of the porphyry was accompanied by the development of much sericite. Quartz phenocrysts were attacked and replaced by sericite and secondary quartz. Schrader (1923, p. 35) described rhyolite which has been completely changed into massive quartz in which all traces of the rock minerals have disappeared except quartz phenocrysts which are recognized by their wine color and other characteristics.

The writer recently examined a mineralized granite in Wisconsin in which the minerals of the granite, with the exception of primary quartz, have been replaced by fine-grained quartz accompanied at places by considerable molybdenite. A rock from Summitville, Colorado, shows corroded quartz phenocrysts such as form only in a porphyry. The groundmass now is at least 95 per cent quartz except where brecciated and cemented by covellite.

The Bonanza district of Colorado (Burbank, 1932, p. 71) furnishes an example of intense silicification not only in the walls of veins but even far outside. Silicia was substituted for the greater part of the original mineral constituents of the volcanic rocks (Fig. 2). Several types of silicified rocks were recognized:

(1) White or grayish rock in which quartz or chalcedony or both are major constituents;
(2) Reddish, brownish, or less commonly black, silicified rock or "jaspers";
(3) White or gray rocks that consist largely of quartz and alunite;
(4) White, grayish-white, or slightly iron-stained rocks in which quartz is principal constituent with some kaolin;
(5) White or grayish-white rocks that consist of a mixture of various proportions of quartz, kaolin minerals and sericite.

Recent studies of alteration of obsidian at the hot springs of Yellowstone Park (Allen and Day, 1935, p. 123) show an addition of 11 per cent silica deposited mainly as quartz.

Many computations of the mineral composition of fresh and altered

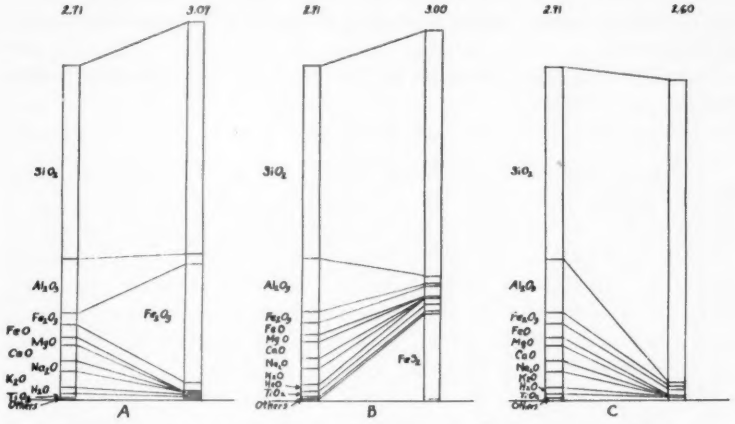

FIGURE 2.—*Gain or loss of principal constituents of augite-mica andesite*

From wall rock, Bonanza district, Colorado. Gain or loss given in grams per 100 cubic centimeters of rock. (A) Black jasper containing hematite. (B) Red jasper. (C) Siliceous altered rock. (After Burbank, 1932, p. 75-76)

rocks have been made where silicification was important. The following table shows the increase in several typical examples.

TABLE 1.—*Quartz in fresh and altered rocks*

Rock	District	Quartz	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Rhyolite	Creede, Colorado	39.9	49.5
Quartz monzonite	San Francisco, Utah	16.2	38.16
Quartz monzonite	San Francisco, Utah	23.16	42.9
Quartz monzonite	Helena, Montana	19.86	42.42
Diorite	Hailey, Idaho	8.45	36.18
Monzonite porphyry	Silverton, Colorado	21.3	60.9

Increase in quartz during hydrothermal alteration does not necessarily mean introduction of silica for a certain amount may be liberated by the alteration of silicates, particularly feldspars. The usual equations

representing the alteration of orthoclase to muscovite or kaolinite illustrates this process very well.

The form in which silica is deposited varies but frequently it seems to be deposited as a colloid later crystallizing to form chalcedony or quartz. Even where colloidal silica was deposited in the early stages, at later stages quartz seems to crystallize directly from solutions, especially in vugs.

Silicification is often dominant in or near veins and sericitization farther out.

SERICITIZATION

The most characteristic mineral change in the hydrothermal alteration of igneous rocks is the development of sericite. This is not only a result of the alteration of potash-bearing primary minerals but also is due, in large part, to the actual contribution of potash by the altering solutions. Thus many minerals other than those carrying potash are replaced by sericite at an early stage, and even ferromagnesian minerals may eventually become largely sericitic. The development of sericite is so common that a complete citation of studies is impracticable. Only a few characteristic or striking examples will be noted. Lindgren (1901, p. 30) gives an excellent summary of the occurrence of secondary muscovite.

Sericitization seems to affect first the soda-lime feldspars. Knopf (1913, p. 56) has described an example of selective sericitization in which the soda-lime feldspars were completely transformed to sericite, whereas orthoclase remained largely unaltered. In other districts orthoclase sometimes becomes highly sericitized, as will be noted. Bastin and Hill (1917, p. 107) state that in Gilpin County, Colorado, the early hydrothermal changes are markedly selective, and a characteristic feature is the replacement of plagioclase phenocrysts by sericite before replacement of the groundmass or orthoclase phenocrysts. Near the veins extensive alteration resulted in complete sericitization of all feldspar, and chlorite and epidote are replaced by sericite as well. In the Hayseed vein plagioclase has been completely converted to sericite and calcite, whereas microcline and quartz are not affected.

Spencer (1917, p. 56) has described the alteration at Ely, Nevada, where the more intense alteration in connection with ore formation results in the progressive destruction of hornblende, plagioclase, and magnetite and the construction of sericite and a brown variety of mica allied to biotite. Pyrite, chalcopyrite, and calcite were deposited in the altered rock.

Not all muscovite which forms during hydrothermal alteration is

the fibrous sericitic variety. Biotite, for example, frequently bleaches or alters to muscovite, presumably by removal of iron. In the Up-to-Date mine in Colorado biotite altered to muscovite with some calcite and small grains of iron oxide. (Bastin and Hill, 1917, p. 117.)

Lindgren (1897, p. 645) states that in a diorite in Idaho a few muscovite foils evidently replaced biotite. At the St. Anthony mine in the Sturgeon Lake gold field of Ontario (Moore, 1912, p. 755) granite near quartz veins has altered to a rock consisting of quartz and muscovite. Close to the vein the rock consists of a yellowish-green, almost greasy mass of scaly mica, believed to be both sericite and paragonite.

Silicic igneous rocks may be largely converted to sericite. Lindgren (1899, p. 177) notes that rhyolite in Idaho was converted by strong hydrothermal action to a nearly pure chalky sericite or mixture of sericite and kaolin. Quartz largely resists sericitization but in extreme cases has been attacked and replaced by sericite. Examples are furnished by the Idaho basin (Lindgren, 1897, p. 640), San Francisco district, Utah (Butler, 1913, p. 75), Miami, Arizona (Ransome, 1919, p. 160), and the Sugarloaf district of Colorado (Schwartz, 1933, p. 537).

Examples of ferromagnesian minerals more or less replaced by sericite are fairly common. Lindgren (1894, p. 274) described an amphibolite at Ophir, California, which altered to sericite with some pyrite, carbonate, chlorite, and sphene. McCann (1922, p. 360) found dark-gray augite diorite bleached to a light-gray rock with abundant sericite replacing chlorite as well as feldspar. Weed (1912, p. 87) noted that in the Butte granite biotite and hornblende altered to chlorite which in turn was extensively replaced by sericite. Emmons and Calkins (1913, p. 175) found that at Philipsburg, Montana, chlorite was present in the early stages but was lacking where alteration was intense. Sericite replaced orthoclase, plagioclase, biotite, and hornblende.

Reber (1916, p. 564) believes sericitization and propylitization are due to similar solutions, but in the more intense alteration sericite replaces the ferromagnesian minerals. Kirk (1912, p. 61) came to the same conclusion from his studies of chloritization and sericitization at Butte.

In the Tyrone district, New Mexico (Paige, 1922, p. 25), granodiorite porphyry was altered at places almost completely to sericite with considerable quartz and minor amounts of other minerals. In the most advanced stages not only are the primary feldspars altered to sericite, but the quartz grains contain sericite blades. Sericite formed from oligoclase, andesine, and labradorite as well as orthoclase.

In the Bonanza district of Colorado (Burbank, 1932, p. 79), sericite alteration has affected all the different types of volcanic rocks. The vein

gouges are made up largely of sericite with some pyrite, quartz, carbonate, and either rutile or anatase. Sericite is believed to have formed during an early stage of vein formation.

Sericite may attack various minerals in an irregular fashion, but there is also, in some cases, a well-defined control by the cleavage or zoning of feldspar. Quartz is characteristically attacked along fractures. The end product is usually a felt of sericite.

The extent of formation of sericite or muscovite is indicated by many calculated mineral compositions. In the San Francisco district, Utah, Butler (1914, p. 427) shows an increase from no muscovite in the fresh rock to 42.98 per cent in altered quartz monzonite 2 to 4 inches from a tourmaline-pyrite-chalcopyrite vein. Several examples are given in Table 2.

TABLE 2.—*Sericite in fresh and altered rocks*

Rock	District	Sericite	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Granodiorite	Lincoln, California	?	41.76
Amphibolite	Ophir, California	?	46.97
Diabase	Grass Valley, California	?	21.20
Granodiorite	Nevada City, California	?	61.46
Monzonite porphyry	Clifton Morenci, Arizona	3.75	44.29
Monzonite porphyry	Ely, Nevada	.00	18.00
Diorite	Hailey, Idaho	.00	38.18
Granite	Willow Creek, Idaho	?	46.84
Quartz monzonite	Helena, Montana	.00	26.86
Quartz monzonite	San Francisco, Utah	1.59	35.02
Trachyte	Rochester, Nevada	?	42.03

BIOTITIZATION

The formation of biotite is evidently not common during the hydrothermal alteration of igneous rocks; it is usually converted to chlorite, magnetite, and pyrite.

In exceptional cases, however, biotite seems to have formed during alteration; thus Lindgren (1901, p. 609) noted that it replaced hornblende and feldspars at Meadow Lake, California, and Rossland, British Columbia, and occurs in small veinlets replacing quartz at the Bunker Hill and Sullivan mine, Idaho. Hatch (1901, p. 7) refers to biotite beds replacing hornblende in the Kolar district of India. Spencer (1906, p. 63) found that a brown diorite from Gold Creek in the Juneau district of Alaska contained much mica; he believed that metasomatic altera-

tion of the green diorite had involved the addition of potash. Later Knopf (1912, p. 37) came to the same conclusion for the nearby Eagle River district, where hornblende was converted to biotite. The mineral composition of altered amphibolite shows 43 per cent biotite as compared with 7.9 per cent in the fresh rock. Spencer (1917, p. 56) also noted the development of a brown mica with sericite at Ely, Nevada.

Barrell (1907, p. 140) sums up the paragenesis of biotite as shown in the contact zone of the Marysville batholith. He says

> "At a greater distance biotite and hornblende are about equally stable, and the partial or complete transformation of hornblende into biotite may therefore be regarded as a mark of hydrothermal metasomatism, though perhaps at a temperature but a little lower than under the more intense conditions closer to the contact."

In rare cases a green or brown secondary biotite similar to sericite develops during hydrothermal alteration. Reber (1916, p. 560) refers to a green mica rock at Clifton-Morenci which resulted from intense alteration, possibly at somewhat higher temperature than that at which sericite developed. The green mica rock consists largely of a finely divided felt of brownish-green biotite with numerous apatite and pyrite masses. Beeson (1913, p. 378) noted secondary biotite where sericite was scarce in the altered quartz monzonite at Bingham, Utah. Butler (1920, p. 166) described a dark phase of altered porphyry at Bingham which contained 29.19 per cent biotite as compared with 5.50 per cent in the fresh porphyry.

PROPYLITIZATION

The most characteristic hydrothermal alteration of basic rocks is propylitization, or the formation of chlorite and epidote, particularly from the ferromagnesian minerals. The process, however, is not limited to basic rocks but may affect the ferromagnesian minerals of the silicic rocks.

Propylitization is defined by Kemp as the alteration of igneous rock in which hydrous magnesian alteration products are important and are associated with epidote and carbonates.

In many silicic rocks the dark silicates alter to chlorite and carbonates, but in advanced stages the chlorite is replaced by sericite. Lindgren (1899, p. 174) has described the intense changes brought about by hydrothermal alteration of basalt in Idaho. The basalt becomes soft and chloritic and acquires pyrite in the early stages. In the advanced stages it is bluish green or yellowish green, owing to epidote. Abundant minerals are: chlorite, quartz, epidote, calcite, and leucoxene. Augite is the first mineral to be attacked.

Probably the most extensive and important example of hydrothermal alteration of basic rocks which may be referred to, in general, as pro-

pylitization, is that of the amygdaloidal tops of basalt flows in the Keweenaw Peninsula of Michigan. The process of mineralization and the mineralogy are complex, but the most conspicuous minerals are epidote and chlorite. Feldspar, chlorite, and epidote formed at an early date in the mineralization (Butler *et al.*, 1929, p. 53), followed by more hydrous minerals such as laumontite, analcite, and saponite. Copper was introduced mainly at an intermediate date and replaced epidote especially. Other minerals include calcite, quartz, pumpellyite, prehnite, datolite, ankerite, sericite, analcite, arsenides, and sulphides, and lastly sulphates.

Lindgren (1901, p. 585) refers to propylitization as especially characteristic of the more basic Tertiary effusive rocks, but the more acidic types are also affected. Deposits at Comstock Lode (Nevada), Nagyag (Hungary), Pachuca (Mexico), Thames (New Zealand), Silver Cliff (Colorado), and Silver City (Idaho) are given as examples.

The earlier andesite at Tonopah (Spurr, 1905, p. 210) at a distance of many feet from the veins has altered to a greenish rock in which chlorite and calcite are abundant. Pyrite and siderite are common. Feldspar has altered chiefly to calcite and a little quartz. Hornblende and pyroxene are altered to chlorite pseudomorphs. The groundmass has also altered to a chloritic material.

At Goldfield (Ransome, 1909, p. 176) propylitization was classed as a third type of alteration not closely associated with the ores. It consisted of the development of calcite, quartz, chlorite, epidote, and pyrite at the expense of the original minerals and groundmass. Andesite, latite, and dacite were thus altered.

The monzonite porphyry (Ransome, 1911, p. 101) at Breckenridge, Colorado, shows some propylitization. Biotite altered to lenses of chlorite with calcite and epidote. Pyroxene and hornblende have been transformed partly or wholly to the same minerals. Feldspars altered partly to calcite, sericite, and kaolinite.

Near the gold-quartz veins of the Allegheny district, California (Ferguson and Gannett, 1932, p. 27), basic rocks were altered at an early stage. Hornblende was replaced by chlorite and epidote, and a micaceous mineral replaced plagioclase. At later stages quartz and carbonate were introduced.

Propylitization is common in the volcanic rocks of the Bonanza district, Colorado (Burbank, 1932, p. 71), particularly in the andesitic lavas. Chlorite, calcite, quartz, epidote, sericite, and rutile are the abundant secondary minerals. The alteration grades into more intense sericitic alteration.

Propylitization has been important near the veins in the deposits of

the Stockton and Fairfield quadrangles of Utah (Gilluly, 1932, p. 93). The ferromagnesian minerals altered to chlorite, epidote, and carbonate. Feldspars altered to epidote, carbonates, and sericite. Pyrite was introduced near the ore deposits.

In the Gold Hill mining district (Nolan, 1935, p. 53) chlorite replaced augite, hornblende, biotite, and plagioclase phenocrysts and cuts the groundmass in irregular veinlets.

In the Bayard area of New Mexico Lasky (1936, p. 58) found that chlorite formed mainly in the second stage of alteration, and biotite and to a lesser extent hornblende altered to chlorite. Epidote formed later, replacing phenocrysts and the groundmass of quartz diorite and granodiorite porphyry, and also formed unusual concretions.

Kirk (1912, p. 42) has carefully described the occurrence of chlorite in altered Butte granite near the copper deposits. The ferric constituents have altered to grayish-green chlorite. Augite and hornblende decomposed early in the alteration, and in their places appeared chlorite, pyrite, epidote, and secondary quartz. Biotite is replaced mainly by chlorite and needles of rutile. Pyrite is closely associated with the chloritic alteration and occupies the outlines of primary femic constituents.

Emmons and Larsen (1923, p. 118) noted that at Creede, Colorado, rhyolite and intrusive porphyry show surprisingly little sericitization, but ferromagnesian minerals have altered to chlorite which has also formed abundantly in the groundmass of both rhyolite and intrusive porphyry. The alteration is summed up by the following statement.

"Briefly the hydrothermal processes at Creede are characterized by the development of much thuringite and a little sericite."

Similar alteration is described for the Mogollon district, Nevada (Ferguson, 1927, p. 54), where the ferromagnesian minerals are altered to chlorite, iron oxide, and calcite, plagioclase is replaced by calcite plus quartz, kaolin, and chlorite, and the groundmass by chlorite and calcite.

SERPENTINIZATION

The role of serpentine in hydrothermally altered rocks is difficult to determine. It seems to be rather generally accepted that ultrabasic rocks commonly alter to serpentine during deuteric action. Presumably such a change may take place in any rock; therefore, where serpentine is present in a hydrothermally altered rock the problem of its origin is naturally difficult to solve. However, there are many minor occurrences of serpentine in hydrothermally altered rocks where the mineral cannot be identified in the rocks not affected by hydrothermal solutions. It seems safe to conclude, therefore, that serpentine does develop during

hydrothermal alteration of basic minerals, but chlorite seems the more common product.

Butler (1913, p. 75) states that in the quartz monzonite at San Francisco, Utah, in the most altered rock magnesium is present as serpentine in small fibrous masses in other minerals.

URALITIZATION

The formation of fibrous amphibole or uralite from ferromagnesian mineral, particularly pyroxene, during hydrothermal alteration of igneous rocks is fairly common. When the change is far advanced the original pyroxene crystals become an aggregate of amphibole needles commonly considered to be hornblende, but other members of the amphibole group may be represented.

Dana (1911, p. 390) notes that the change of pyroxene to amphibole was first described by Rose in 1831 in rocks from the Ural Mountains. Since that time the change has been recognized by innumerable investigators. Uralite is, however, not a stable product of hydrothermal, or of other types of alteration for that matter, and so in turn alters to or is replaced by chlorite, sericite, or other minerals.

Uralitization is apparently not characteristically hydrothermal in origin but also takes place during metamorphism of various types. Van Hise (1904, p. 274) says:

> "However, perhaps the most frequent and characteristic of the alterations of the diopside-augite series is uralitization or change to amphibole. This process is particularly characteristic of the ancient igneous rocks, and especially those which are under comparatively deep seated conditions, although the alteration is by no means confined to deep seated rocks."

Reber (1916, p. 544) states that the diabase at Morenci, Arizona, shows extreme alteration to fibrous green hornblende.

CARBONATION

Carbonates such as calcite, dolomite, ankerite, siderite, manganosiderite, and rhodochrosite, particularly as vein fillings, often form during hydrothermal activity. Lindgren (1894, p. 278) describes this process at Ophir, California. He says:

> "The extensive carbonation of the Ophir wall rocks is very remarkable indeed, especially as the main fissures are almost completely filled with quartz and contain very little or no carbonate."

Lindgren (1901, p. 90) tabulates the mineralogical composition of four altered rocks from gold-quartz veins which show the following percentages of carbonates: Plantz vein, Placer County, California, granodiorite 32.96 per cent; Ophir, Placer County, California, amphibolite 25.47 per

cent; Bellefountain mine, Nevada City, granodiorite 10.51 per cent; and Grass Valley, California, diabase 48.86 per cent.

At Tonopah (Spurr, 1905, p. 208) andesite was intensely altered, and much of the original pyroxene, hornblende, biotite, and magnetite appears to be replaced by siderite and pyrite. Siderite was observed pseudomorphic after pyrite but often is contemporaneous.

At Cripple Creek (Lindgren and Ransome, 1906, p. 187) dolomite and calcite are abundant in the various hydrothermally altered igneous rocks. Ferromagnesian silicates and orthoclase have been partly replaced by carbonate, and magnetite by siderite. Dolomite and pyrite are the most abundant introduced minerals in altered latite-phonolite. Altered volcanic breccia was calculated to contain 7.37 per cent carbonate.

In the Hauraki gold field of New Zealand Finlayson (1909, p. 632) found siderite derived from chlorite and magnetite.

One of the most careful studies of the formation of carbonates during hydrothermal alteration is that by Ransome (1911, p. 99) for the Breckenridge district, Colorado. In the alteration of diorite porphyry the rocks close to the vein contained 29.3 per cent carbonates, with siderite, magnesite, rhodochrosite, and calcite molecules in order of abundance.

In the Philipsburg district (Emmons and Calkins 1913, p. 175) in the granite wall rock of silver veins, calcite replaced biotite, hornblende, plagioclase, and orthoclase. Calcite predominates over quartz in the wall rock, and the reverse is true in the veins.

Calcite is abundant throughout the altered andesite at Oatman, Arizona (Ransome, 1923, p. 38).

The writer (Schwartz, 1923, p. 99) found carbonate surprisingly abundant in the Ely greenstone of Minnesota which is composed of a series of much altered basalt flows. Sericite, chlorite, and other minerals suggest that hydrothermal alteration, as well as regional metamorphism, has been important. Plagioclase particularly has been replaced by carbonate.

In the Mother Lode district (Knopf, 1929, p. 43) the wall rock near the veins is nearly solid ankerite which resulted from the replacement of greenstone. At places ankeritized augite crystals still preserve the original zoning. Hydrothermally altered greenstone contains 35.46 per cent ankerite.

The Allegheny district, California (Ferguson and Gannett, 1932, p. 39), has the carbonate stage as the important stage of wallrock replacement, with ankerite, sericite, mariposite, and minor amounts of other minerals developed in serpentine and gabbro.

In the quicksilver deposits of Oregon (Wells and Waters, 1934, p. 30)

andesitic lavas are cut by carbonate veins, and alteration products are important. Hypersthene is abundantly replaced by siderite. Two types of veins are recognized—silica-carbonate veins and sericite-carbonate veins.

In the Bayard area of New Mexico (Lasky, 1936, p. 62), calcite replaces all primary minerals in various intrusive rocks, irrespective of composition.

Other districts in which carbonate has been introduced during the hydrothermal alteration of igneous rocks include Helena, Montana (Knopf, 1913, p. 55), Idaho Basin (Lindgren 1897, p. 640), and the Mogollon district of New Mexico (Ferguson, 1927, p. 54). The formation of carbonate is referred to at least casually in the majority of descriptions of hydrothermal alteration.

PYRITIZATION

The formation of pyrite is characteristic of the hydrothermal alteration of igneous rocks. In the early stages at least, pyrite seems to form by the combination of iron of the ferromagnesian minerals with sulphur from the hot solutions. Magnetite also contributes its quota of iron. With more intense alteration pyrite may replace practically any mineral.

To list or review occurrences in detail is unnecessary since most hydrothermally altered igneous rocks contain pyrite, but a few typical examples indicate the importance of pyritization.

Butte furnishes such an example (Weed, 1912, p. 91). Comparatively fresh quartz monzonite contains .04 per cent pyrite as calculated from analyses, whereas the hydrothermally altered rock contains from 4 to 6 per cent. The fresh rock has as much as 1.25 per cent magnetite which is converted to pyrite. Kirk (1912, p. 46) has noted particularly the pyritization of former ferromagnesian areas in the Butte granite (quartz monzonite). He shows that the ferromagnesian mineral contained enough iron to furnish the observed pyrite in the outlines of those minerals, but not enough for all of the pyrite in the rock. As a result of experiments as well as the observations referred to, Kirk states:

> "The conditions of these experiments are believed to be sufficiently analogous to those present during pyritization—and chloritization and sericitization—at Butte to warrant the statement that the ferrous silicates and perhaps the magnetite could have been decomposed by hydrogen sulphide, alkaline sulphides or carbonates, or possibly caustic alkalies, and the iron converted simultaneously into pyrite by the sulphides mentioned, or by fumarolic or solfataric action."

Becker (1882, p. 210) described the occurrence of pyrite in the Comstock Lode area, where its amount is about proportional to the degree of alteration. Many of the pseudomorphs after the ferromagnesian silicates

are studded with pyrite, and some appear to show real pseudomorphs of pyrite after augite or hornblende.

Recently the writer (Schwartz, 1933, p. 537) described the alteration of a Colorado granite. The original rock shows no pyrite in thin sections, but the altered rock is sericitic, and chemical analysis indicates that it contains 6.7 per cent pyrite.

At Tyrone, New Mexico (Paige, 1922, p. 27), silicification and sericitization were accompanied by pyritization and the introduction of copper. Paige says:

> "There is every reason to believe that the sulphur needed to form pyrite was an element in the solutions which carried the potash necessary for the formation of sericite."

Iron also is believed to have been introduced.

Spurr (1905, p. 207) noted that at Tonopah pyrite and siderite followed the outlines of original hornblende or biotite.

Pyrite developed abundantly in the altered rocks at Cripple Creek (Lindgren and Ransome, 1906, p. 185) as small crystals in the groundmass as well as in the phenocrysts or the minerals of granular rocks.

In the monzonite porphyry at Breckenridge, Colorado (Ransome, 1911, p. 100), feldspar phenocrysts were peculiarly susceptible to pseudomorphous replacement by aggregates of pyrite, sphalerite, and galena. Biotite

TABLE 3.—*Pyrite developed in several altered rocks*

Rock	District	Pyrite*	
		Fresh rock	Altered rock
		(Per cent)	*(Per cent)*
Andesite	Bonanza, Colorado		24.96
Melaphyre	Mother Lode, California	.00	2.74
Diorite	Juneau, Alaska	.96	2.10
Monzonite	Helena, Montana		6.73
Granodiorite	Lincoln, California		1.61
Granodiorite	Nevada City, Nevada	.02	2.87
Andesite	New Zealand		3.13
Dacite	New Zealand		4.69
Porphyry	Rio Tinto, Spain		1.27
Quartz monzonite	Clifton-Morenci, Arizona	.24	3.09
Granite	Cripple Creek, Colorado	.12	4.78
Latite	Cripple Creek, Colorado		4.65
Diorite porphyry	Breckenridge, Colorado	.09	1.99
Gneiss	Freiberg, Germany		4.26
Dacite	Goldfield, Nevada		7.20
Latite	Silverton, Colorado		7.19
Monzonite porphyry	Ely, Nevada		3.11

* Blank spaces represent very small amounts.

also altered to sericite and was partly replaced by the same sulphides. Examples of this sort might be multiplied many times. Table 3 indicates the extent of formation of pyrite in several examples of alteration.

ALBITIZATION

Gilluly (1933) has recently described in detail the albitization of zones in a quartz diorite and gives an extensive review of the process. The occurrence near Sparta, Oregon, however, is due to late magmatic or possibly deuteric alteration. It is clear that no sharp line can be drawn between this type and the undoubted hydrothermal alteration. Most of the examples appear to be essentially deuteric in origin. A few which do not appear to be deuteric are included here.

Excellent examples of hydrothermal albitization have been described by Spencer (1906, p. 10) and by Knopf (1912, p. 38). The original rock of the Treadwell mines, Alaska, contains albite-oligoclase phenocrysts with albite and prisms of hornblende in the groundmass, with various amounts of interstitial microperthite and accessory apatite, zircon, magnetite, and rutile. The secondary feldspar is invariably albite and is usually free from decomposition, giving the rock a fresh appearance. Albite has formed at the expense of the microperthite and also fills narrow seams which cut across the original feldspar. Other secondary minerals are uralite, green mica, chlorite, epidote, zoisite, calcite, quartz, sericite, rutile, pyrite, pyrrhotite, with rare molybdenite, sphalerite, chalcopyrite, and arsenopyrite. Analyses of three phases of somewhat altered albite diorite show a soda content ranging from 5.09 to 10.01 per cent. If the lower figure represents the approximate original content a very decided addition of soda is indicated. The albite content ranges from 47.68 to 84.36 per cent.

Knopf (1912, p. 36) gives considerable detail on albitization in the Juneau belt; he found a large increase in albite in an altered diorite and in amphibolite and gabbro. The relatively unaltered rock contained a calculated content of 18.3 per cent albite, whereas the altered rock contained 39.3 per cent. Referring to altered amphibolite Knopf says:

> "Under the microscope the altered rock is found to be composed mainly of albite, with minor amounts of quartz, pyrite, carbonate, chlorite and accessory apatite."

Recently Lasky (1936, p. 56) has found secondary albite important in the Central Mining District, New Mexico. It occurs in all the igneous rocks of the district except Tertiary lava flows and is replaced by other alteration minerals. Lasky considers that it represents the earliest hydrothermal alteration. In quartz diorite and granodiorite porphyry the original feldspars are albitized, and the degree of albitization seems to depend on the permeability of the rocks.

McCann (1922, p. 350) has noted secondary albite in the extreme phase of alteration of augite diorite of the Bridge River district, British Columbia.

Rocks in which albite has formed during alteration are fresh in appearance in contrast to the more common bleached and softened appearance of sericitized rocks for example. The anhydrous character of albite suggests higher temperature of formation or possibly less water available for hydration. Not all soda crystallizes as albite in hydrothermal alteration. Probably albitization is prominent at higher temperatures under conditions which favor dehydration. At lower temperature and with more hydrous conditions, paragonite develops as has been noted particularly by Moore (1912, p. 756) in the St. Anthony mine.

ALUNITIZATION

Alunite is developed in many districts as a distinctive hydrothermal mineral. The known American occurrences in 1912 were summarized by Butler and Gale (1912, p. 38), and numerous references are scattered throughout descriptions of mineralized areas published since 1912.

The occurrence of alunite at Goldfield, Nevada (Ransome, 1907, p. 667; 1919, p. 176), is probably the most important example of the mineral resulting from the hydrothermal alteration of igneous rocks. It is generally associated with the intense alteration of the rocks in the vicinity of the ore bodies and also is widespread in rhyolite, dacite, and andesite. Its occurrence in the ore zones is much like that of kaolinite. In the rhyolite, feldspar phenocrysts as well as the groundmass have been altered to a soft aggregate of quartz-kaolinite-alunite and pyrite. Altered dacite is calculated to contain 15.73 per cent alunite. Alunite is one of the most characteristic minerals of the deposit.

At Rosita Hills, Colorado (Cross, 1891, p. 466), a rhyolite is highly altered to alunite, the altered rock consisting of about one-third alunite and two-thirds quartz.

The extensive deposits of alunite in New South Wales are believed by Pittman (1901, p. 419) to have resulted from extreme alteration of rhyolite by steam and sulphurous acid vapors accompanying the intrusion of dolerite.

In sulphur deposits in Nevada (Adams, 1904, p. 500) alunite is found in cavities in the rock formations where feldspar especially has been altered by solfataric action.

The remarkable deposit of alunite near Marysvale, Utah (Butler and Gale, 1912, p. 7), is a vein filling, but alunite is also found in the volcanic wall rocks where it develops as platy crystals in feldspar which is at

places converted to a felted mass of alunite and quartz. Associated minerals are mainly quartz and sericite.

Colorado, especially the San Juan region, seems to have particularly abundant alunite. Cross and Larsen (1935, p. 125) have noted this for the region as a whole. Larsen (1913, p. 181) described its occurrence with secondary quartz in highly altered breccia, rhyolite, quartz latite, and andesite rocks of the San Cristobal quadrangle. Burbank (1932, p. 73) found alunite in a jaspery mass replacing rhyolite in the Bonanza district and in the Rico Mountains. Cross and Spencer (1900, p. 92) described a porphyry altered to a rock consisting largely of alunite with kaolinite and quartz. Patton (1917, p. 50) has described in some detail its occurrence in the Platoro-Summitville district. Andesite, andesite breccia, and latite specimens show considerable amounts of alunite with quartz and kaolin. Analysis of the andesite breccia shows high alumina, potash, combined water, and sulphate radical. It was calculated that the rock contained about 32 per cent alunite.

In the Black Hills (Grout and Schwartz, 1927, p. 369) alunite has been described in an altered porphyry where it replaced feldspar and formed rims around pyrite.

Particularly noteworthy is the occurrence at Cerro de Pasco (Graton and Bowditch, 1936, p. 659) where much alunite was formed during the intense phase of alteration of a quartz monzonite porphyry. Alunite and kaolinite developed at the expense of sericite which had replaced feldspar, biotite, and hornblende. It is emphasized that alunite and kaolinite were never seen directly replacing fresh feldspar. At places alunite is replaced by kaolinite (dickite).

Alunite has developed abundantly in the lavas surrounding hot springs in Lassen Volcanic National Park according to Anderson (1935, p. 242). It replaces plagioclase or is scattered evenly through the rock.

The known occurrences of alunite as an alteration product of igneous rocks indicate that it forms most abundantly at relatively shallow depths. It is rare at moderate depths and unknown in the high-temperature deposits. The potash is not infrequently derived from potash feldspar, but some examples clearly require the assumption that introduced potash played an important role.

KAOLINIZATION

The extent of development of kaolinite and allied minerals during hydrothermal alteration of igneous rocks is a debatable point. It is difficult to determine in many deposits whether the kaolin minerals were developed during hydrothermal alteration or as a result of weathering. The problem has been extensively reviewed by Ross and Kerr (1930,

p. 170). They point out that there are three kaolin minerals, and that, as a rule, no distinction has been made between them. This is certainly true in practically all of the papers reviewed by the writer. Considering the kaolin group as a whole—*i. e.*, as including kaolinite, dickite, and nacrite—there are several examples in the literature which seem to indicate a hydrothermal origin.

Ransome (1901, p. 128) has described the formation of considerable kaolinite and diaspore in the monzonite porphyry wall rock at Silverton, Colorado. The composition of the altered rock, as calculated from chemical and microscopical data, shows 26.3 per cent diaspore.

Ransome (1907, p. 690) also described kaolinite in intimate association with alunite, gold, and sulphides at Goldfield, Nevada, and believed it to be of the same origin as the gold. Analysis of altered dacite indicates 23.99 per cent kaolinite. Ransome also stated that the mineral occurs as an undoubted primary constituent in some San Juan ores.

Patton (1917, p. 48) noted the development of a kaolin mineral, especially at a distance from the veins, in the Platora-Summitville area of Colorado. Burbank (1932, p. 73) found an essentially similar occurrence in the nearby Bonanza district, where silicification and kaolinization are believed to have been early stages of the alteration. At places the alteration was more complex, and diaspore and zunyite were formed.

In the altered granite of the Ray and Miami districts of Arizona (Ransome, 1919, p. 138) kaolinite is developed in situations strongly indicating a hydrothermal origin, which is further shown by the fact that sericite replaces kaolinite which is pseudomorphous after feldspar.

Many have believed that the great china clay deposits of western England owe their origin to magmatic solutions, but Ross and Kerr (1931, p. 174) reject this explanation. These authors, however, report that dickite from the island of Anglesey and from Red Mountain, Colorado, may have been formed by hydrothermal solutions and they show that at higher temperatures dickite is more stable than true kaolinite. They conclude that dickite is most commonly of hydrothermal origin. Nacrite, the third of the kaolin minerals, is also of possible hydrothermal origin. Their conclusion regarding nacrite is as follows:

> "This confirms the evidence of the mineral relations which indicates that these samples of nacrite were formed by hydrothermal or gas-phase reactions, but the two occurrences of nacrite known do not give sufficient evidence for generalization on the genetic origin of this mineral."

The writer's impression, gained from an extensive review of hydrothermal alteration, is that one or more of the kaolin minerals form not uncommonly during hydrothermal alteration, usually, however, as a

subordinate constituent. It is not always possible to assign the origin to hypogene solutions with certainty, but many investigators have indicated their preference for this origin in spite of the fact that most kaolinite has been considered a product of weathering. Fenner (1936, p. 293) believes that clay formed by two processes in the upper Geyser Basin of Yellowstone Park: near the surface by the attack of acid sulfate and at depth by the attack of CO_2 in an alkaline solution.

Cerro de Pasco, as already noted, affords an excellent example of abundant kaolinite (dickite) formed in the most intense phase of hydrothermal alteration. Both minerals persist to the greatest depth reached in mining.

APATITIZATION

In general apatite is one of the most stable primary minerals during hydrothermal alteration. In reviewing the literature, one encounters repeatedly the statement that apatite remains unaltered. Occasionally destruction of apatite is noted. However, Knopf (1912, p. 37) has described an occurrence in the Eagle River district, Alaska, where apatite seems to have been introduced. The apatite occurs as long slender needles traversing a succession of contiguous minerals, and the abundance of apatite appears to increase with increase in amount of alteration. Apatite was also found in minute veinlets traversing the altered rocks. The essentially unaltered amphibolite contained apatite as a rare accessory mineral. Calculation of the mineral composition from chemical analyses shows an increase in apatite from .6 per cent to 1.2 per cent.

In altered basic dikes at Cripple Creek (Lindgren and Ransome, 1906, p. 193) apatite is remarkably abundant as slender greenish-white prisms of different habit from the primary apatite. It is stated that obviously phosphoric acid has been added to the original dike rock.

ADULARIA

Adularia has been formed in several districts during hydrothermal alteration of igneous rocks but it is usually not abundant. It forms more often as a vein filling than as replacement masses. It is mentioned repeatedly in the list of secondary minerals but rarely is it an important enough constituent to receive special description.

Both adularia and secondary orthoclase are terms used to describe potash feldspar in veins and replacements. Economic geologists as a rule seem to use the term adularia where the rhombic habit is developed and the term secondary orthoclase where the rhombic form is not evident.

Adularia is mentioned as widespread in small amounts in the ore deposits of New Mexico (Lindgren, 1910, p. 71) and is found in the San

Juan district, Colorado, National Mining district, Nevada, Marysvale, Utah, Mohave County, Arizona, Jarbridge, Tonopah, and Gold Springs, Nevada.

At Tonopah (Spurr, 1905, p. 208) adularia is a common gangue mineral intercrystallized with quartz. The Mizpah Hill andesite is intensely altered to quartz, sericite, and adularia. The alteration of soda-lime feldspar to adularia is common, but feldspar is more commonly altered to sericite and quartz, in which case adularia is usually not present. Spurr says:

> "The alteration of the soda-lime feldspar to adularia can be observed in all its stages in different rock specimens. The alteration proceeds along the edges and the cleavage cracks of the crystals, so that the brightly polarizing andesine, somewhat turbid from decomposition, becomes reticulated with the fresh glassy adularia, which shows markedly lower polarization colors. Characteristic complete or incomplete crystals of adularia with rhombic outline frequently form within the older crystal. In some cases the alteration is completely carried out and the feldspar is completely pseudomorphosed to adularia whose perfect crystal outlines give the idea of a fresh primary crystal, but whose optical characteristics prove the truth of the change demonstrated in other cases by observed transitions."

Adularia is an important alteration product in the quartz monzonite of the Bingham district, Utah, a justly famous case of hydrothermal alteration.

Burbank (1933, p. 69) notes the occurrence of adularia in the Bonanza district, Colorado, in quartz-rhodochrosite-fluorite veins, as altered veinlets cutting country rock, and especially in altered latite country rocks.

At Cripple Creek (Lindgren, 1898, p. 418) adularia occurs as a vein filling but more abundantly as a replacement especially in altered granite. Sericite sometimes developed with it but is more abundant in altered volcanic rocks. A characteristic feature of the alteration of the granite is the abundant solution of orthoclase and microcline and reprecipitation as typical adularia.

Adularia is no doubt a typical hydrothermal mineral, but potash feldspar may occur abundantly as more nearly normal orthoclase as in the deposits of Climax, Colorado (Butler and Vanderwilt, 1933, p. 228), where secondary orthoclase is exceedingly abundant. It has also been shown to be abundant in the rocks altered by waters of the hot springs of Yellowsprings Park (Fenner, 1936, p. 240) where soda and lime of the original feldspar were replaced by potash, forming orthoclase.

TOURMALINIZATION

Tourmaline is not a characteristic hydrothermal mineral but forms most abundantly during igneous and contact or pneumatolytic activity. However, some occurrences seem related to high-temperature hydrothermal activity. Knopf (1913, p. 47) has described in some detail an

example of tourmalinization of a quartz monzonite in the Helena district, Montana. The quartz monzonite is altered to sericite and impregnated with sulphides. Tourmalinization evidently proceeded from the joint planes in the monzonite; where joints were closely spaced, the igneous rock was completely altered to a quartz tourmaline rock. Near these zones the monzonite was altered to a coarse quartzose rock containing considerable glassy sericite as fine scales with pyrite, arsenopyrite, sphalerite, and galena. The association of tourmaline with sericite seems ample justification for considering this particular tourmaline of hydrothermal origin.

Butler (1913, p. 75) states that small crystals of tourmaline were noted in altered wall rocks of the San Francisco district, Utah.

Tourmaline was also noted under the microscope in altered trachyte at the Rochester district of Nevada (Knopf, 1924, p. 54). Quartz, sericite, and sulphides are associated hydrothermal minerals.

In certain hypothermal veins tourmaline is common, not only in the veins but as a metasomatic product in feldspar and quartz. It is confined mainly to cassiterite and gold-copper-tourmaline vein deposits. Its occurrence in tourmaline-gold-copper veins has been discussed by Lindgren (1901, p. 641), who refers to deposits at Tamaya and La Condes (Chile), Passagem (Brazil), Meadow Lake (California), and Telemarken (Norway).

FLUORITE

Fluorite is a characteristic gangue mineral in a number of hydrothermal deposits, particularly of the epithermal type. It occurs in veins in limestone and in igneous rocks in the western mining districts of the United States. Review of the descriptions of igneous rocks indicates that fluorite is predominantly a fissure filling rather than an alteration or replacement product in the igneous rock. Exceptions occur, however, as at Cripple Creek (Lindgren and Ransome, 1906, p. 123), where fluorite appears as a product of replacement of various igneous rocks. It is found, for example, in altered latite-phonolite with pyrite and dolomite, replacing pyroxene. The final result is, in some cases, a purple quartz-fluorite-pyrite rock.

Johnston (1928, p. 90) notes that a volcanic agglomerate in New Mexico has been somewhat replaced by fluorite.

Lindgren (1901, p. 654) states that fluoritic gold-tellurium veins are characterized by an intense metasomatic action with the gangue mainly quartz, fluorite, and barite.

In a recent extensive review of the occurrence of fluorite in the western states Lindgren (1933, p. 163) has described many occurrences in igneous

rocks, but most of these are vein fillings rather than metasomatic replacements. Fluorine is shown to be related to the alkaline rocks of the Rocky Mountain region.

OTHER MINERALS

A great many minerals occur occasionally in hydrothermally altered igneous rocks. Among these may be mentioned particularly various sulphides, hypogene oxides, a great many silicates, a few sulphates, and perhaps other mineral groups. Experience in the field, as well as review of the literature, indicates that most of these are not of widespread importance; locally one or more may be important, but such restricted examples need not all be reviewed in a general study of hydrothermal action.

In hypothermal tin deposits topaz is an important constituent of some greisens. It is associated with muscovite, quartz, tourmaline, and lesser amounts of many other minerals. Topaz is probably deposited under near pneumatolytic conditions but Lindgren (1933, p. 638) prefers to call the solutions liquids. Some writers describe them as deuteric.

CHEMICAL CHANGES

GENERAL STATEMENT

In this treatment of chemical analyses the rocks have been subdivided into acidic, intermediate, and basic types. The limiting percentages of silica used are those suggested by Hatch (1926, p. 194) who classifies all rocks containing less than 52 per cent silica as basic, those with silica content between 52 and 66 per cent as intermediate, and those above 66 per cent as acidic. That some such subdivision is desirable is scarcely open to question. The chemical composition of the fresh rock is certain to have a profound effect upon the course of alteration as is clearly demonstrated by facts brought out in the present paper.

The use of the intermediate subdivision as well as the common division into acidic and basic groups seems desirable for several reasons. Perhaps most important is the fact that ore deposits are more often associated with rocks of intermediate composition. Thus 49 analyses of altered intermediate rocks were available for comparison with those of fresh equivalents, whereas only 11 basic and 20 acidic rock pairs are available. Another reason for the subdivision is that the threefold subdivision simplified plotting and study of results.

The discussion of chemical changes is based primarily on a series of analyses of 57 fresh and 80 hydrothermally altered rock equivalents. These analyses were tabulated by pairs on separate sheets. All calculations involving chemical changes for each pair were then tabulated on

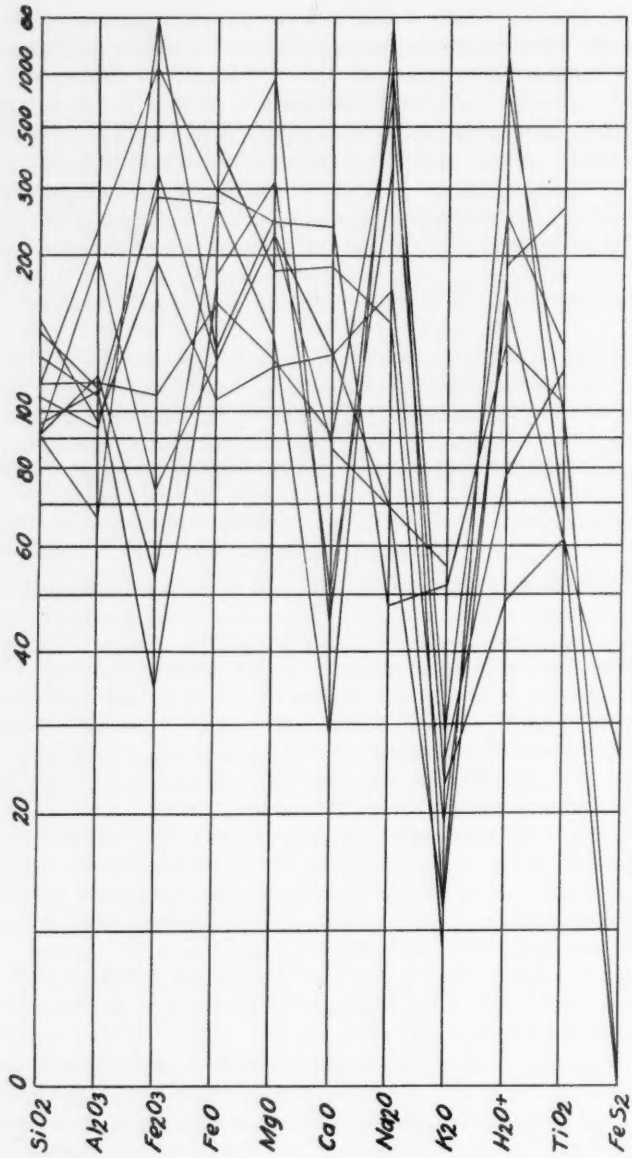

FIGURE 3.—*Relative gains and losses during hydrothermal alteration of basic igneous rocks*

this sheet. All quantitative mineralogical data for the same analyses were put on the reverse side of the sheets. This made the work of sorting and comparing or contrasting various groups easy.

The percentage of each chemical constituent of the fresh rock was divided by the percentage in the altered rock and the result multiplied by 100. The data were then plotted on the straight-line diagrams divided into acidic, intermediate, and basic groups. It was planned, at first, to publish these composite diagrams, but the great number of lines—47 for some parts of the intermediate group—made this impractical. Nevertheless these diagrams were of great use in studying the analyses and making deductions. Figure 3, the composite diagram for the basic rocks and the simplest of the three groups, is published as an example.

The calculations plotted on Figure 4 representing net gains and losses require explanation. As already noted the analyses were sorted on the basis of the composition of the fresh rock into acidic, intermediate, and basic types. The percentages of each of the 10 leading oxides were then averaged for the fresh rocks and for the altered rocks of each type. Thus the composition of the average fresh rock and average altered rock of each type was obtained (Table 4), and these were then compared graphically (Fig. 4). The net gains and losses for the average of all rocks as shown by Figure 4 were obtained by taking the mean of the acidic, intermediate, and basic lines on the diagram. The average of all fresh rocks and all altered rocks was also computed and when plotted on the straight-line diagram compared favorably with the mean of the three.

TYPES OF DIAGRAMS

Numerous types of diagrams have been used to represent chemical changes in the hydrothermal alteration of igneous rocks. Some are suitable for one purpose, others for another purpose. It is, perhaps, safe to say that none are entirely satisfactory, but most of them aid greatly in bringing out changes which can be grasped from the analyses only by tedious study.

In this general study the writer has adopted the straight-line diagram, used and explained by Leith and Mead (1915, p. 288); no other diagram permits such extensive use of multiple data. It also has the advantage of not requiring assumptions of any sort and does not pretend to make absolute comparison but simply indicates relative changes. To interpret this diagram, it is only necessary to remember that the figures at the top represent the number of grams of altered rock required to contain the same weight of a given oxide as 100 grams of the fresh rock; relative gains, therefore, are indicated left of the 100 line and relative losses to the right.

Two types of circular diagrams have been used to illustrate changes during hydrothermal alteration. Steidtmann (1908, p. 384) illustrates one type, and Ransome (1909, p. 181) the other. Ransome (1911, p. 97) also used a rectilinear coordinate diagram for comparing analyses at different distances from a vein in the Breckenridge district. Columnar diagrams are simple and effective means of illustrating both chemical and mineral changes as shown for example in papers on the Climax molybdenum mine, Colorado (Butler and Vanderwilt, 1933, p. 224) and the Bonanza district, Colorado (Burbank, 1932, p. 74–76). Figures 1 and 2 are adapted from the latter publications. Spurr (1905, p. 218–219) used the relative length of horizontal lines to show changes in amounts of the common elements during eight stages of alteration of the earlier andesite at Tonopah. The same stages are also compared graphically by means of the Brögger diagram (1898, p. 255).

Most of the diagrams referred to are illustrated and described by Leith and Mead (1915, p. 288–298).

CALCULATION OF GAINS AND LOSSES

Many careful studies of gains and losses during hydrothermal alteration have been made. It was shown very early by Lindgren (1900, p. 218-231) that not only were complete rock analyses necessary but also the determinations of specific gravity both in bulk and in powder. In addition, field observations regarding possible volume changes are also essential, if calculations are to be made as to absolute gains and losses. Grout (1926, p. 512–538) has recently made a critical analysis of the various computations which have been made and points out the proper methods as well as the pitfalls.

Early in the present study it was found that utilization of only those analyses which were combined with adequate specific gravity and other determinations would defeat the general purpose of the paper. It was therefore decided to make purely relative comparisons of the percentage of each constituent. It must be realized, therefore, that the differences between percentages given (Tables 5 to 12) does not mean an absolute introduction or elimination of the constituent in the amount of the difference between percentages. The percentages indicate merely the relative amounts present in a given weight of each rock.

The calculations of gains and losses as well as mineral compositions calculated from the analyses will be found in many of the references cited.

SUMMARY OF CHEMICAL DATA

The average fresh-rock analysis obtained by averaging the percentages of each principal constituent of the 57 fresh analyses is compared

in Table 4 with Clarke's average igneous rock. This average is close enough to Clarke's to indicate that it is fairly reliable. The average for the 80 altered rocks derived from the 57 fresh rocks is shown in the third column. The relative gains and losses are indicated by Figure 4.

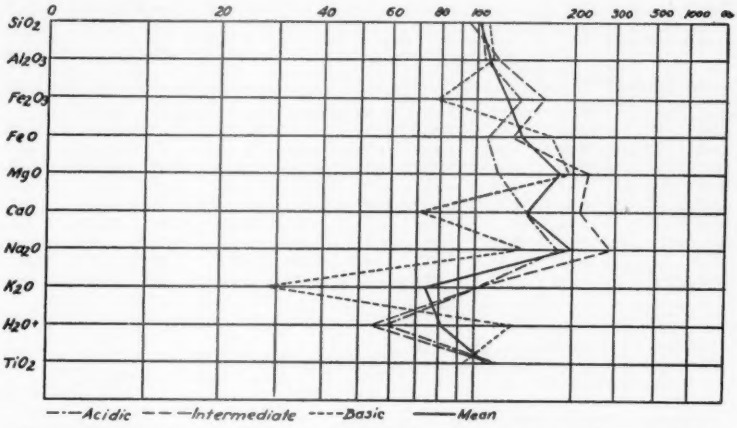

FIGURE 4.—*Net gains and losses during hydrothermal alteration of igneous rocks*

The average fresh and altered acidic, intermediate, and basic rocks are also shown in Table 4.

Figure 4 shows the net changes which result from hydrothermal alteration. By net change is meant the average of all changes—that is, both gains and losses. These may be briefly summarized as a basis for detailed discussion. Silica and alumina show relatively little net change in the three groups and the mean of the three. This results from some losses balancing other gains. Ferric oxide shows a moderate loss except in the basic rocks which show a gain presumably due to oxidation of ferrous iron; ferrous oxide shows about the same net loss in all types of rocks as does magnesium oxide. Lime shows a net loss in acidic and intermediate rocks and the mean of the three but shows a gain in the basic rocks. It is suspected that this indicated gain in lime is not dependable but is a result of carbonation, which was important in the rocks from which the few available analyses were made. More analyses are needed for basic rocks. Soda shows a relative net loss under all conditions, whereas potash shows little net change in acidic and intermediate rocks but a pronounced gain in the basic group. Water shows a gain except in the basic rocks. Titanium shows little change.

Net changes have little significance regarding individual occurrences but they do emphasize the fact that any constituent may show either a gain or loss during hydrothermal alteration depending on conditions which prevail during the process.

TABLE 4.—*Averages of 10 most important oxides in fresh and altered igneous rocks* *

	1	2	3	4	5	6	7	8	9
SiO_2	59.14	61.75	62.63	70.02	68.62	61.27	64.34	47.82	44.07
Al_2O_3	15.34	15.81	14.30	15.32	14.57	16.19	14.21	15.81	14.30
Fe_2O_3	3.08	2.26	1.81	1.36	1.03	2.44	1.54	3.21	4.09
FeO	3.80	3.52	2.46	1.48	1.38	2.85	2.27	8.25	4.91
MgO	3.49	2.74	1.21	.77	.67	2.30	1.01	6.99	3.60
CaO	5.08	4.17	3.19	1.26	.90	4.41	2.09	8.63	12.08
Na_2O	3.84	3.12	1.29	2.19	1.24	3.39	1.20	2.34	1.72
K_2O	3.13	3.41	3.62	4.71	4.54	3.59	3.59	.62	2.08
H_2O+	1.15	1.54	2.27	.97	1.64	1.35	2.47	2.73	2.14
TiO_2	1.05	.73	.63	.42	.36	.75	.64	.93	.98

1. Clarke's average igneous rock
2. Average of 57 fresh rocks used in this paper
3. Average of 80 hydrothermally altered equivalents of fresh rocks of 2
4. Average of fresh acidic rocks
5. Average of altered acidic rocks
6. Average of fresh intermediate rocks
7. Average of altered intermediate rocks
8. Average of fresh basic rocks
9. Average of altered basic rocks

* These analyses were not recalculated to 100 per cent because in some cases constituents such as iron sulphide formed an important part of the altered rocks.

SILICA

Silica shows relatively minor net change in hydrothermal alteration in any of the rocks, but some analyses show wide variations from the average. Silicification, as might be expected from the mineralogical data given earlier in this paper, furnishes the most pronounced change. Chemical analyses of altered rocks from Climax and the Bonanza district, Colorado, indicate replacement of all other constituents by silica (Fig. 5). Calculations based on specific gravity show that the apparent gain in silica and the loss in other constituents is a real one (Butler and Vanderwilt, 1933, p. 225; Burbank, 1932, p. 78). The importance of the introduction of various forms of quartz has been referred to under silicification.

At Bonanza (Burbank, 1932, p. 71)[1] silicification is one of the most prominent and characteristic effects of hydrothermal alteration and in its simplest form is characterized by the substitution of silica for the greater part of the original constituents of the volcanic rocks. The

[1] The description by Burbank is one of the most comprehensive on silicification. Those particularly interested should refer directly to the paper.

silicification is believed to belong to an earlier part of the hydrothermal activity which produced the ores.

Spurr (1905, p. 218) has shown that silica was introduced during the alteration of the Tonopah andesite and even replaced earlier introduced potash. He says (1905, p. 224):

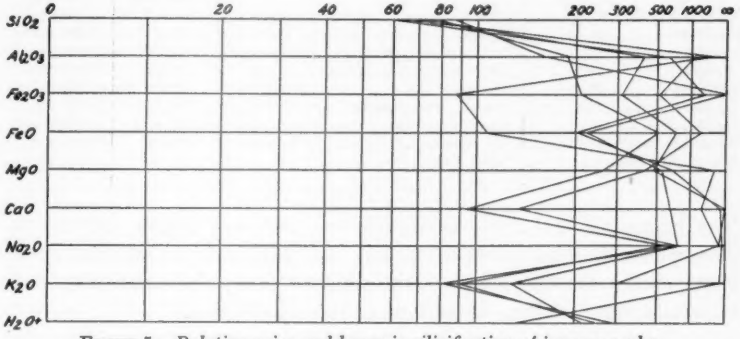

FIGURE 5.—*Relative gains and losses in silicification of igneous rocks*

"It appears from this that the increased activity of the altering solutions as indicated in the above figures, has begun to attack some of the introduced potash and to replace it by silica, or, perhaps, rather that the balance is more in favor of strong silicification than the introduction of potash."

At Silverton, Colorado, Ransome (1901, p. 123) calculated a considerable increase in silica in a latite on the basis of constant volume of altered rock compared with that of the unaltered as indicated by the lack of porosity or by evidence of contraction in bulk. Monzonite porphyry in the same district also shows a considerable increase in silica during hydrothermal action.

Finlayson (1909, p. 635) states that progressive silicification was very marked in the Hauraki gold fields of New Zealand. Fresh hornblende dacite adjoining a vein had 76.61 per cent, silica and replacement ore along the vein had 85.65 per cent.

The following table lists examples of relatively large increases in silica.

Several examples of hydrothermal alteration of igneous rocks show considerably less silica in the altered rocks than in the fresh rocks.

The diorite porphyry at Breckenridge, Colorado (Ransome, 1911, p. 96) shows a distinctly lower percentage of silica near the vein than 25 feet from it. The percentage of silica in the fresh rock 25 feet from the vein is 57.35 and in the altered rock 6 inches from the vein it is 46.62.

TABLE 5.—*Silica in analyses of fresh and altered rocks*

Rock	District	Silica	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Granite	Climax, Colorado	70.83	98.23
Trachyte	Tonopah, Nevada	67.69	91.40
Trachyte	Rochester, Nevada	67.01	74.58
Andesite	Bonanza, Colorado	57.62	88.73
Andesite	Bonanza, Colorado	57.62	95.18
Dacite	Hauraki, New Zealand	63.45	85.65
Latite	Silverton, Colorado	55.61	64.79
Monzonite porphyry	Ely, Nevada	58.78	73.61
Monzonite porphyry	Tintic, Utah	59.76	71.14

The grams per 100 cubic centimeters of rock are 158.46 and 136.59. An increase in MgO, FeO, CO_2, and H_2O suggests the substitution of these oxides for the silica. Mineralogical study indicates that carbonates are particularly important in the substitution.

Lindgren (1901, p. 89) gives an interesting series of four pairs of analyses from gold-quartz veins. In each pair the altered rock contains a lower percentage of total silica in spite of the importance of quartz in the veins. This is accounted for by the destruction of silicates of high SiO_2 content and the formation in their place of sericite and carbonates. Quartz is attacked but in no case is it completely replaced by the sericite carbonate aggregate.

A similiar example, described by McCann (1922, p. 362), is in the Bridge River, British Columbia, district, near quartz-gold veins. In augite diorite there is 49.34 per cent silica in the fresh rock and 35.06 per cent in the altered, or a relative loss of 15.34 grams of silica per 100 grams of fresh rock. Carbonates form an important percentage of the altered rock.

Knopf (1929, p. 43), after studying the alteration of greenstone by ore-forming solutions in the Mother Lode system of California, states that near the veins the greenstones are commonly solid ankerite rocks, and as the ankeritization has affected large volumes of rocks it is clear that enormous quantities of silica have been removed from the wall rocks.

It seems clear from these examples that a large loss in silica occurs mainly where CO_2 is introduced. This is brought out by comparing the analyses cited by Knopf. Constituents other than silica, carbon dioxide, and potash show only nominal differences. Silica is lost, and potash and carbon dioxide increase greatly. Some examples of a decrease in silica by alteration are shown in Table 6.

TABLE 6.—*Altered rocks showing a decrease in silica*

Rock	District	Silica	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Granite	Sugarloaf, Colorado	72.80	62.39
Granodiorite	Nevada City, California	66.65	56.25
Diorite porphyry	Breckenridge, Colorado	57.35	46.62
Granodiorite	Lincoln, California	65.54	46.13
Quartz-monzonite	Butte, Montana	64.03	54.30
Augite melaphyre	Mother Lode, California	49.24	34.17
Amphibolite	Ophir, California	45.56	37.01
Augite diorite	Bridge River, British Columbia	49.34	35.06

ALUMINA

Alumina is considered the most stable of the abundant oxides in rocks but it is probably less stable during hydrothermal alteration than during normal weathering. The net change as brought out by Figure 4 is slight for acidic, intermediate, and basic rocks, as a result of a balance between several rather striking gains and losses. Increase in alumina may be only apparent, owing to the leaching of other constituents, but in some examples adequate consideration of specific gravity and porosity leaves no doubt of absolute changes. In considering alumina it must be remembered that the percentages are of very little use for determining gains or losses of alumina unless total iron and titanium as well as phosphorus have also been determined in the same analysis.

The problem of alumina was discussed by Ransome (1901, p. 121) in connection with analyses of rocks from the Silverton district, Colorado. He concluded that the most reasonable assumption indicated addition of alumina during the hydrothermal alteration of a latite.

At Cripple Creek (Lindgren, 1906, p. 194) altered granite in which adularia is important contains somewhat more alumina than the fresh rock. This does not necessarily suggest contribution as the change is small (14.33 to 16.00 per cent), but at least alumina was retained mainly in adularia.

At the St. Anthony mine in the Sturgeon Lake gold district of Ontario a very notable increase in alumina has been shown by Moore (1912, p. 756). The freshest granite contains 17.11 per cent alumina, and the most altered 27.38 per cent. The increase is accounted for mineralogically by a high content of sericite and paragonite.

The percentage of alumina is larger after alteration in several rocks, but recalculation on the basis of specific gravity often indicates little

change. This has been well shown by Butler (1913, p. 76) for four pairs of analyses of quartz monzonite and emphasizes the necessity of considering percentage changes as relative only.

A considerable increase in alumina during albitization of amphibolite has been shown for the Eagle River region, Alaska (Knopf, 1912, p. 39). The percentages of alumina for fresh rocks is 13.59 and for altered rocks 20.53. Gain in the alteration of 100 cubic centimeters of amphibolite to same volume of altered product is 17.7 grams. In terms of its own mass in the unaltered amphibolite, this is 42.2 per cent. Since no decided volume change is indicated this suggests an important addition of alumina.

As noted, alumina has long been considered the most stable oxide in rock alteration, and particularly in weathering it is often assumed for purposes of comparison that it remained constant. The same assumption has sometimes been made in considering hydrothermally altered rock, but this has largely been discarded as unsafe. A review of the unquestionable losses of alumina during rock alteration justifies the discarding of this practice.

An excellent series showing progressive decrease in alumina is given by Finlayson (1909, p. 638) from the Waihi mine, New Zealand. Fresh hornblende dacite contains 15.26 per cent alumina. Chloritized dacite 45 feet from the vein contains 16.51 per cent. From this distance to the vein a series of four analyses shows progressively less alumina to 1.35 per cent in the replacement ore of the vein. Silica was added in large amounts and replaced all other constituents of the unaltered rock.

A similar condition is found at Tonopah (Spurr, 1905, p. 226) where a progressive decrease in alumina is noted from 16.4 per cent in the average type of andesite to 4.31 in the vein material. Spurr says:

> "This shows the further continuation of the changes in the preceding analyses, the alumina and potash being gradually removed to make way for the increasing silica."

Diorite porphyry (Ransome, 1911, p. 96) at Breckenridge shows a decline of alumina with intensity of alteration; a positive loss is indicated after corrections for specific gravity. The same is true for the monzonite porphyry at Ely, Nevada (Spencer, 1917, p. 57), where the porphyry ore contains 10.23 per cent alumina as compared with 17.85 per cent in the fresh monzonite porphyry. At Breckenridge carbonates largely replaced the aluminous minerals. At Ely silica largely replaced the bases and alumina, especially in feldspar.

At Grass Valley, California (Lindgren, 1901, p. 89), diabase shows 11.89 per cent alumina in the fresh rock and 5.29 per cent in the altered

phases. Carbonate shows a striking gain, in this case particularly calcium carbonate.

The Bonanza district of Colorado (Burbank, 1932, p. 78) shows an unusual degree of elimination of alumina with 15.84 per cent in the fresh rock and a minimum of .97 per cent as a result of silicification.

Practically complete elimination of alumina is indicated in the most intensely silicified zone of the molybdenum deposits at Climax, Colorado (Butler and Vanderwilt, 1933, p. 31).

In conclusion it may be stated that many igneous rocks show little change in the alumina content during hydrothermal alteration, but there are a few well-studied examples of increases, some with good evidence of actual addition. Several examples of decreased alumina are known, especially in connection with silicification.

IRON AND ITS COMPOUNDS

Although iron occurs as two oxides and a sulphide in rocks, it will be most convenient to treat them together. To get a true picture of the action of the element iron in contrast to ferrous and ferric oxides, it is necessary to calculate total iron, as has been done by Leith and Mead (1915, Plate V) for their composite diagrams. In the present study the total iron has been calculated for each of the analyses, but the data were not shown on the diagrams because of a desire to keep them as simple as possible.

Composite diagrams were used to study the behavior of ferric and ferrous oxides. In basic rocks where iron is most abundant, ferric oxide is sometimes lost and sometimes gained to a considerable extent, but ferrous iron is always lost. The average of basic rocks (Fig. 4) shows a gain in ferric oxide and a loss in ferrous oxide. With respect to total iron of the basic rocks seven pairs of analyses show large losses in the altered rock and four show small gains. It seems safe to conclude that there is a loss in total iron during hydrothermal alteration of basic rocks.

A review of the analyses of fresh and altered intermediate rocks shows that ferric oxide may be either gained or lost to a marked extent, but the number of losses greatly exceeds the number of gains. Ferrous oxide shows few gains and many losses. This tendency for the iron oxides to decrease is accounted for by the formation of pyrite—FeS_2 of the diagram. The average (Fig. 4) shows a decided tendency for loss of ferric oxide and a smaller loss for ferrous oxide. Owing to retention of iron in sulphides total iron changes very little in the average of intermediate rocks.

The acidic rocks also show considerable differences in behavior of ferric and ferrous oxide; both show prominent gains in some rocks and

losses in others. Total iron shows more gains than losses. The small amount of iron in the average fresh acidic rock doubtless makes it easier for hydrothermal solutions to add iron, especially in the development of pyrite.

The most conspicuous examples of addition of iron are furnished by two altered andesites from the Bonanza district, Colorado (Burbank, 1932, p. 78) (Fig. 2). The first has turned to a black jasper which contains hematite and shows an increase in total iron from 5.13 per cent to 23.95 per cent. Burbank says regarding this rock:

> "Analysis 5 represents an unusual type of nearly black siliceous rock collected from a zone of strong silicification in the Rawley drainage tunnel. It contains abundant hematite and probably represents a zone in which ferric iron has been precipitated from solutions that have effected the silicification and leaching of adjacent or perhaps more or less distant bodies of rock. Besides silica and ferric iron small amounts of barite have apparently been added from the solutions."

Other phases of the alteration of this same rock show a loss of iron during intense silicification. The second rock, also an altered andesite, shows an increase of total iron from 5.13 per cent to 14.17 per cent, the increase being due to the formation of about 25 per cent pyrite in the altered rock.

The altered granite of the Sugarloaf district of Colorado (Schwartz, 1933, p. 543) shows a large increase in total iron, owing to the introduction of pyrite. A similar example is found in monzonite porphyry at Morenci (Lindgren, 1905, p. 168).

The monzonite at Bingham, Utah, shows a decided increase of iron mainly as pyrite; Boutwell (1905, p. 178) believed part of this was introduced. A similar case is found in the quartz monzonite of the Helena, Montana, district (Knopf, 1913, p. 50).

Butte (Weed, 1912, p. 91) furnishes a classic example of pyritization. The normal fresh rock contains from .04 to .07 per cent pyrite, whereas the altered rock contains from 4 to 6 per cent.

Diorite porphyry at Breckenridge, Colorado (Ransome, 1911, p. 96), shows a large increase of total iron as ferrous oxide, owing mainly to the formation of siderite.

Diabase at Grass Valley, California (Lindgren, 1901, p. 666), shows a decided loss of total iron near the gold-quartz veins, owing apparently to the replacement of the ferromagnesian minerals by muscovite.

At Tonopah (Spurr, 1905, p. 210), trachyte has been noticeably silicified with a considerable decrease in the total iron, and in the advanced stage of alteration of the earlier andesite iron has disappeared.

The monzonite porphyry at Ely, Nevada (Spencer, 1917, p. 57), shows a loss in total iron during sericitization; this was accompanied by the formation of copper ores.

At Juneau, Alaska, a considerable loss in iron occurred during albitization.

LIME

The lime (CaO) content of igneous rocks is usually decreased during the alteration of acidic and intermediate rocks, although there are several exceptions. Basic igneous rocks more commonly show a gain or a moderate loss. The net result for all igneous rocks is a loss (Fig. 4). It may be suspected that the apparent gain in the basic rocks is a result of too few analyses, several of which happen to be examples of carbonation. At least one is entitled to the opinion that a quantitative study of all types of hydrothermal alteration of basic rocks would show a loss as in acidic and intermediate rocks. Gains and losses during several cases of carbonation are shown by Figure 8.

Lindgren (1901, p. 666) cites four pairs of analyses of rocks near gold-quartz veins; three pairs show a much higher CaO content in the altered rock with a corresponding increase in CO_2, showing that the lime became fixed mainly as carbonate.

The porphyry of the Huelva district, Spain, has been altered to a marked degree, according to Finlayson (1910, p. 407), and analyses show an increase in CaO from 1.15 in the fresh rock to 2.28 per cent in the altered.

The Rawley andesite of the Bonanza district, Colorado, shows a probable increase in CaO in an incipient phase of alteration, but the advanced stages show complete elimination in some specimens (Burbank, 1932, p. 78).

TABLE 7.—*Altered rocks showing increase in lime*

Rock	District	CaO	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Andesite	New Zealand	5.69	8.11
Monzonite	Ajo, Arizona	.76	1.88
Basalt	Keweenaw Point, Michigan	6.94	9.37
Basalt	Keweenaw Point, Michigan	7.46	15.56
Quartz diorite	Bayard, New Mexico	5.99	6.93
Granodiorite	Lincoln, California	4.88	10.68
Amphibolite	Ophir, California	2.30	9.78
Porphyry	Rio Tinto, Spain	1.15	2.28
Augite mica andesite	Bonanza, Colorado	4.81	6.62
Diabase	Grass Valley, California	10.36	28.85
Granite	Cripple Creek, Colorado	1.39	2.03
Quartz monzonite	Butte, Montana	4.20	7.36

Near the Ophir vein of the Hauraki gold fields there is a somewhat erratic increase in CaO from the unaltered hornblende andesite to the altered andesite near the vein.

Increase in CaO in the altered rock is not always as carbonate. Lindgren (1906, p. 194) gives comparative data on fresh and altered granite from Cripple Creek which shows an increase of CaO from 1.39 per cent to 2.03 per cent with an indicated decrease in CO_3 from .36 per cent to .26 per cent.

Examples of a loss in percentage of CaO in altered rocks relative to fresh rocks are so numerous that only the more conspicuous examples are listed in Table 8.

TABLE 8.—*Altered rocks showing decrease in lime*

Rock	District	CaO	
		Fresh rock	Altered rock
		(Per cent)	*(Per cent)*
Amphibolite	Eagle River, Alaska	11.09	4.76
Quartz monzonite	San Francisco dist., Utah	5.31	.29
Latite	Silverton, Colorado	5.85	.43
Monzonite porphyry	Ely, Nevada	4.31	.31
Quartz diorite	Ajo, Arizona	5.06	1.19
Andesite	Bohemia district, Oregon	3.83	.66
Monzonite porphyry	Bingham, Utah	5.37	1.18
Quartz monzonite	Helena, Montana	3.28	.05
Quartz monzonite	Bolivia	3.07	.37
Dacite	Goldfield, Nevada	5.84	.41
Quartz monzonite	Butte, Montana	4.20	.05

Review of these occurrences shows that silica, soda, potash, ferric iron, and ferrous iron have each been added in one or more of the examples of a relative increase in lime. It is especially during extreme silicification and sericitization that lime is reduced. In incipient or moderate sericitization lime may be gained.

MAGNESIA

The magnesia (MgO) content of igneous rocks during hydrothermal alteration changes considerably, but the net result is a loss. The average altered rock contains only about half as much MgO as the original, and when one considers that many cases of incipient alteration are included in the averages it can be appreciated that the tendency in well-advanced cases is to eliminate the magnesia. Nevertheless in a few altered rocks magnesia has been gained. Composite diagrams show that

these cases are limited to intermediate and acidic rocks—to those not originally high in magnesia. Appreciable gains in MgO are indicated by analyses from the following areas: Ajo (Arizona), Breckenridge (Colorado), Hauriki (New Zealand), and Caracoles (Bolivia). The gain in MgO is accompanied by a gain in ferrous oxide and water, indicating the formation of hydrous magnesium-iron silicates of the chlorite group—*i.e.*, propylitization. One of the most complete studies is that by Ransome (1911, p. 94) on the rocks at Breckenridge. Diorite porphyry shows that MgO was 2.41 per cent in the fresh rocks and 4.02 per cent in the altered rocks 6 inches from the vein. In per cent of original rock mass the change is from 2.41 to 4.25 per cent. The magnesium-bearing minerals in this example, however, are carbonates rather than silicates.

Finlayson (1909, p. 632) has described the alteration of andesites and dacitic lavas and tuffs in the Hauraki gold fields of New Zealand to a propylitic type. Two stages are recognized: in the first the primary ferromagnesian minerals are replaced by pseudomorphs of green fibrous chlorite, while the plagioclase remains fresh or is altered to carbonates and sericite; in the later stage the chlorite is destroyed, and carbonates become important. The chloritized hornblende andesite contains 3.09 per cent MgO as compared with 2.19 per cent in the fresh rock. Specimens taken at 14 feet, 5 feet, and adjoining a vein show a progressive decrease in MgO to 1.43 per cent near the vein. Other examples of a probable gain in magnesia are shown in Table 9.

TABLE 9.—*Fresh and altered rocks showing increase in magnesia*

Rock	District	MgO	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Granite	Land's End, England	.45	.72
Granite	Sugarloaf, Colorado	.18	.49
Diorite porphyry	Breckenridge, Colorado	2.41	4.02
Monzonite	Ajo, Arizona	1.40	2.14

Loss of magnesia occurs especially during silicification and sericitization of the rock masses. The tendency for chlorite and other ferromagnesian minerals to disappear during advanced stages of alteration has been emphasized by several writers. Sericite especially replaces the hydrous ferromagnesian silicates formed at an early stage. A few examples of conspicuous losses are shown in Table 10.

TABLE 10.—*Fresh and altered rocks showing decrease in magnesia*

Rock	District	MgO	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Diabase	Grass Valley, California	8.87	.94
Diorite	Gold Creek, Alaska	9.07	3.92
Basalt	Keweenaw dist., Michigan	8.32	2.70
Granite	Cripple Creek, Colorado	.89	.03
Andesite	Bonanza, Colorado	2.14	.05
Monzonite porphyry	Bingham, Utah	3.84	.03
Diorite	Juneau, Alaska	1.71	.06
Dacite	Goldfield, Nevada	2.73	.06

SODA

Composite diagrams as well as the averages show that soda is usually lost during the hydrothermal alteration of igneous rocks. The percentage of loss is least in the basic rocks, which are low in soda to start with. The mean of all rocks indicates a loss of about 50 per cent of the original soda content, the indicated change varying slightly with the method of calculation. Of the pairs of analyses studied only 9 show more soda in the altered rock; in 71 pairs it remained nearly constant or, more commonly, showed less in the altered rock.

Examples of a gain in soda are furnished by the process of albitization already referred to (Fig. 6). An analysis of albite diorite from the Treadwell mine (Spencer, 1906, p. 101), which shows much secondary albite, contains 10.01 per cent Na_2O as compared with 5.69 per cent in a less altered phase. An altered amphibolite from the Eagle River region shows 4.67 per cent soda as compared with 2.16 per cent in the relatively unaltered amphibolite. Knopf (1912, p. 39) says:

> "Albitization is a form of thermal hydrometamorphism characteristic of the Alaska gold belt and appears to have been independent of the original amount of soda in the altered wall rocks."

He also states (Knopf, 1929, p. 45) that soda was introduced in the wall rock of the Mother Lode veins of California and formed albite.

Soda does not necessarily occur as albite in altered rocks but probably is common in small amounts as paragonite occurring with sericite.

Moore (1912, p. 756) has shown by analyses that soda increases progressively as the vein is approached in the granite wall rock of the Sturgeon Lake gold field of Ontario. The wall rock at the vein contains 5.12 per cent soda and .74 per cent potash with only sericite and paragonite visible to account for the two oxides.

Table 11 emphasizes the quantitative aspect of the common loss of soda. Most of these losses occur in rocks which show extensive gains in silica or potash or both. Rocks showing carbonation also characteristically show a great loss in soda (Fig. 8). The loss of soda during hydro-

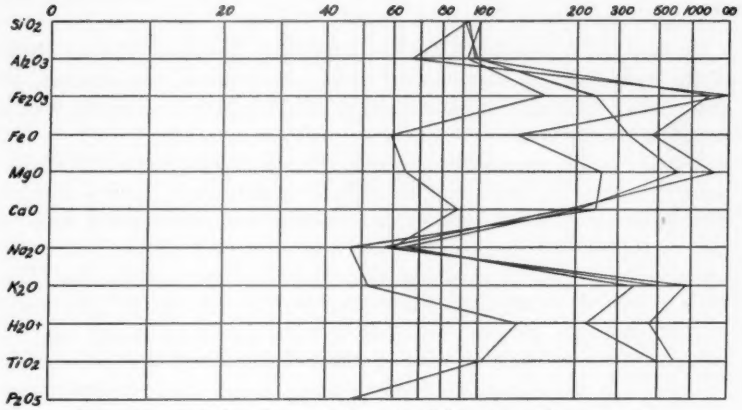

FIGURE 6.—*Relative gains and losses in albitization of igneous rocks*

TABLE 11.—*Fresh and altered rocks showing decrease in soda*

Rock	District	Na_2O	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Granite	Climax, Colorado	2.44	.31
Quartz monzonite	San Francisco, Utah	5.33	.15
Granite	Sugarloaf, Colorado	3.00	.12
Granodiorite	Nevada City, California	3.40	.30
Granodiorite	Lincoln, Placer County, California	4.09	.17
Trachyte	Tonopah, Nevada	2.54	.06
Granite	Land's End, Cornwall	2.69	.27
Monzonite porphyry	Clifton-Morenci, Arizona	5.33	.12
Amphibolite	Ophir, California	1.57	.13
Diabase	Grass Valley, California	4.17	.11
Latite phonolite	Cripple Creek, Colorado	7.80	.62
Monzonite porphyry	Ely, Nevada	3.24	.04
Andesite	Bohemia, Oregon	4.18	.17
Monzonite porphyry	Bingham, Utah	3.60	.37
Quartz monzonite	Helena, Montana	3.08	.39
Diorite	Hailey, Idaho	3.25	.10
Hornblende dacite	New Zealand	2.21	.28
Quartz monzonite	Butte, Montana	2.76	.08
Monzonite porphyry	Tintic, Utah	2.01	.07

thermal alteration indicates that paragonite, the sodium-bearing equivalent of sericite, is not particularly stable under the conditions normally present. The lack of stable hydrous soda minerals is no doubt an important reason for the solution of the element in both hydrothermal alteration and weathering.

POTASH

An increase in potash (K_2O) has long been considered characteristic of the hydrothermal alteration of rocks. This serves, for example, to characterize hydrothermal alteration in contrast with weathering, where potash is usually lost.

A study of the composite diagrams (Fig. 3) shows that all available pairs of analyses of fresh and altered basic igneous rocks show a decided gain in potash. Many intermediate igneous rocks also show a definite gain in potash, but others show a loss and the same is true of the acidic rocks. The net result of all varieties of hydrothermal alteration (Fig. 4) is a gain of potash for basic rocks with little change for the acidic and intermediate groups. In other words fresh rocks fairly high in potash are not so likely to have it added during alteration, presumably because it is not needed to form minerals stable under hydrothermal conditions. Apparently the common generalization that potassium is added during hydrothermal alteration is not so valid as is often supposed, for there are too many exceptions. A consideration of what actually takes place in several examples may serve to emphasize the actual situation. Since a loss of potash is somewhat exceptional in hydrothermal alteration, losses will be considered first.

The losses of potash listed are due to dominance of processes such as silification and carbonation. Thus at Bonanza the loss in some rocks is due to the elimination of all other constituents except silica with the introduction of exceptional amounts of iron and sulphur to form pyrite (24.96 per cent). In several other samples from Bonanza, the reduction in potash is due to intense silicification without pyritization.

Pyrite is the principal substitute for potash and other losses in an altered latite at Silverton, Colorado. At Ely, Nevada, both silica and pyrite increased largely, whereas potash and other bases practically disappeared. It has been observed in several examples of alteration that potash may increase during the early stages and then decrease as other processes, particularly silicification, become dominant.

In some exceptional cases soda is substituted for potash, for example at Juneau, Alaska, and the Sturgeon Lake district, Ontario.

Gains in potash (K_2O) during hydrothermal alteration are so common that the list of all examples would be too long. A few which show either

TABLE 12.—*Fresh and altered rocks showing decrease in potash*

Rock	District	K_2O	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Granite	St. Anthony mine, Ontario	3.00	.75
Latite	Silverton, Colorado	3.77	.24
Monzonite porphyry	Ely, Nevada	4.06	.06
Andesite	Bonanza, Colorado	4.95	.15
Trachyte	Rochester, Nevada	11.42	4.47
Diorite	Juneau, Alaska	3.90	.39
Quartz monzonite	Helena, Montana	4.32	Trace

a large increase in percentage of K_2O present or in total amount are listed in Table 13.

TABLE 13.—*Fresh and altered rocks showing increase in potash*

Rock	District	K_2O	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Augite melaphyre	Mother Lode, California	.88	4.63
Diorite	Gold Creek, Alaska	.20	1.76
Diorite	Hailey, Idaho	2.20	4.79
Granodiorite	Nevada City, California	2.65	6.01
Granodiorite	Lincoln, California	1.95	5.30
Latite-phonolite	Cripple Creek, Colorado	5.83	13.36
Monzonite porphyry	Bingham, Utah	4.23	7.02
Monzonite porphyry	Ely, Nevada	4.16	8.26

The potash added is most commonly combined as sericite, but at places orthoclase, adularia, and alunite account for considerable additions (Fig. 7).

Climax, Colorado, furnishes a good example of increased potash in the form of orthoclase, but this is eliminated by a later stage of intense silicification.

The conspicuous gain in potash in the Cripple Creek latite (Lindgren, 1906, p. 190) is due to the formation of both sericite and adularia. Soda is almost entirely eliminated during the change.

Sericite is abundant at Ely, Nevada, and Bingham, Utah. Sericitization, however, does not always involve a gain in potash, but the potash of the feldspars may simply be converted to sericite. Some well-known examples show no gain and may even show a loss.

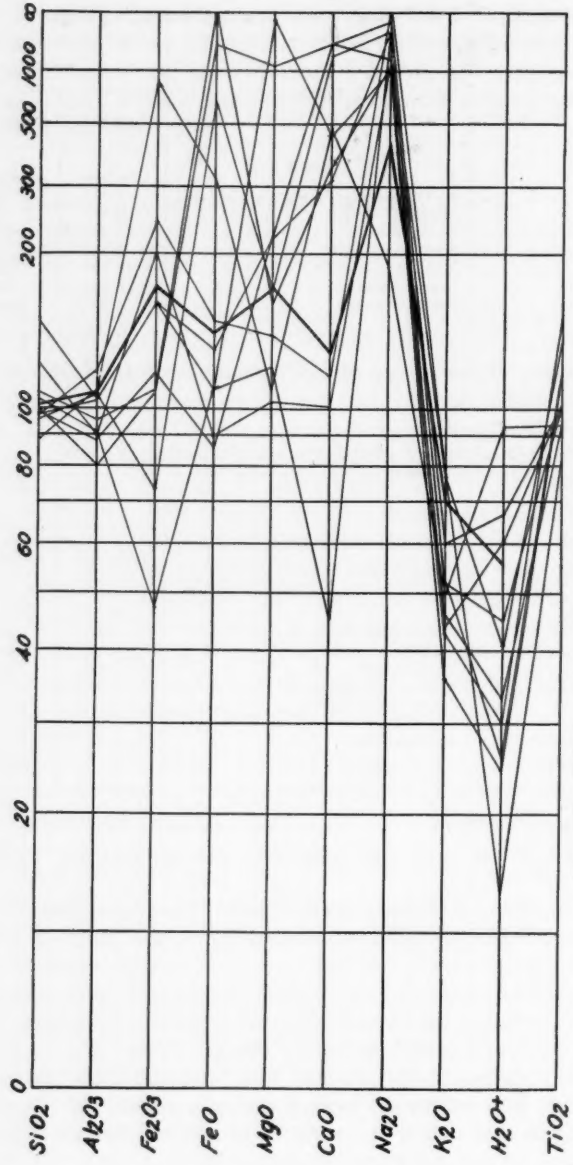

FIGURE 7.—*Relative gains and losses in sericitization of igneous rocks*

Heavy line is average of 40 samples.

The detailed studies of hydrothermal alteration at the hot springs of Yellowstone Park have shown the importance of substitution of potash for soda. Allen and Day (1935, p. 123) show that in drill cores of altered obsidian 3.07 parts of potash have been added and 2.02 parts of soda subtracted for each 100 parts of rock.

WATER

If it were possible to obtain perfectly fresh igneous rocks for comparison with the hydrothermally altered rocks, there would, no doubt, be few pairs that would not show a gain in combined water. Many of the freshest available rocks, however, are somewhat altered, and therefore in cases of silicification, albitization, and carbonation, a loss, or at least no gain, in combined water is shown. Nevertheless the composite diagrams of relative gains and losses show a decided gain in water, and the diagrams of net gains and losses for the acidic, intermediate, and average rocks show gains. The basic rocks show a net loss, but this is because of the inclusion of amphibolites as fresh rock for comparison with mineralized equivalents.

It is clear from microscopic as well as chemical studies that hydrous minerals characteristically develop early during hydrothermal alteration. Thus an anhydrous feldspar becomes hydrous sericite, paragonite, kaolinite, alunite, or epidote. Anhydrous pyroxene, amphibole, and olivine become hydrous chlorite, serpentine, talc, and limonite. Slightly hydrous biotite becomes more hydrous chlorite.

The more intense effect of silicification results in a loss of combined water particularly as compared with the incipient stages which often are characterized by the development of sericite and other hydrous minerals. Burbank (1932, p. 76) notes that in very siliceous rocks in the Bonanza district from which sericite and kaolin minerals are absent there has been a marked dehydration of the lavas.

CARBON DIOXIDE

The importance of carbonation in certain examples of hydrothermal alteration has already been noted, and the addition of CO_2 is shown in Figure 8.

Even though carbon dioxide takes part in the alteration, an increase of CO_2 in the altered rock is not a necessary result because of the solubility of some of the resulting carbonates, particularly sodium and potassium carbonate. Carbonates which remain range from practically pure calcite to dolomite, ankerite, siderite; the acid combines with lime, magnesia, ferrous oxide, and to a lesser extent manganese oxide. Where

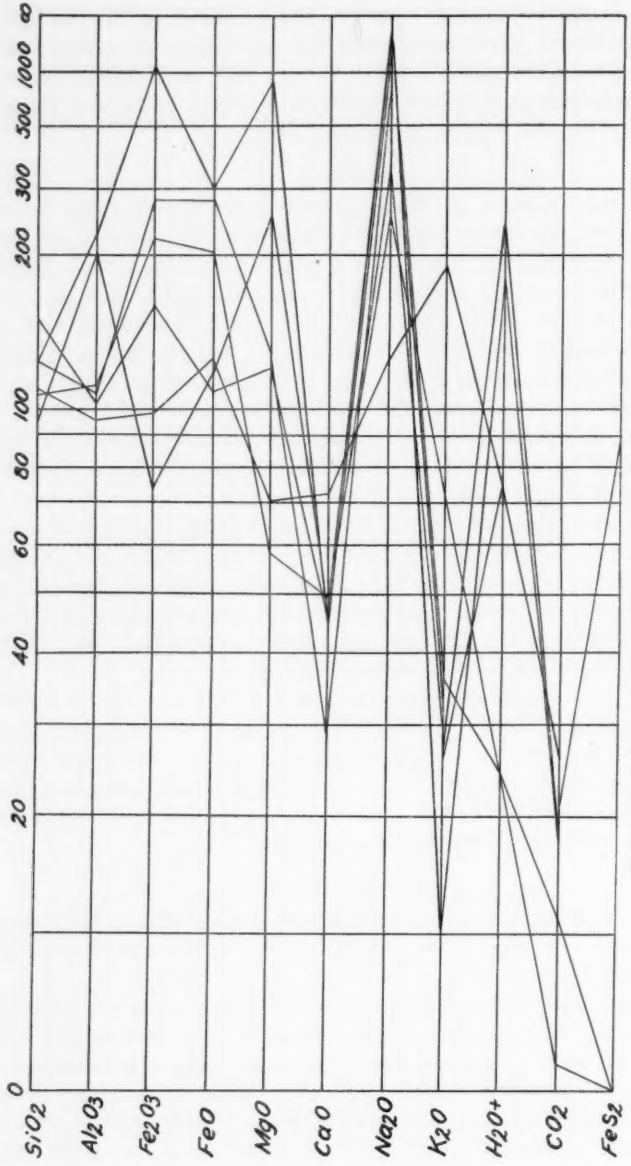

FIGURE 8.—*Relative gains and losses in carbonation of igneous rocks*

silicification or chemical processes other than carbonization have dominated carbon dioxide does not remain in the rock.

Locally igneous rocks may have been almost entirely replaced by carbonate as has been observed in the Ely greenstone of Minnesota, but such examples do not seem to have been studied quantitatively. Where replacement is far advanced, it is naturally difficult to be certain of the extent of alteration or replacement in contrast to deposition in open spaces.

The extent of carbon dioxide additions as well as their prevalence is indicated in Table 14.

TABLE 14.—*Fresh and altered rocks showing gain in carbon dioxide*

Rock	District	CO_2*	
		Fresh rock	Altered rock
		(*Per cent*)	(*Per cent*)
Augite melaphyre	Mother Lode, California	.90	15.50
Amphibolite	Ophir, California	3.04	15.04
Diabase	Grass Valley, California		18.91
Diorite	Gold Creek, Alaska		8.47
Augite diorite	Bridge River, British Columbia	.42	14.72
Amphibolite	Kaalgoorlie, Australia		8.02
Granodiorite	Nevada City, California		4.82
Porphyry	Rio Tinto, Spain	.09	5.08
Granite	Snowmass, Colorado	.20	2.03
Diorite porphyry	Breckenridge, Colorado	.46	11.48
Monzonite poprhyry	Bingham, Utah	.00	2.01
Quartz monzonite	San Francisco, Utah		1.93
Diorite	Juneau, Alaska	.90	2.01
Quartz monzonite	Helena, Montana	.49	1.50
Granodiorite	Lincoln, California		11.24
Granite	Willow Creek, Idaho	.25	3.07
Diorite	Hailey, Idaho	.15	2.86
Porphyry	New Zealand	.09	5.08

* Blank spaces represent very small amounts.

LESSER CHEMICAL CONSTITUENTS

Dependable data on changes of chemical constituents other than the ten discussed are not abundant. Frequently the amounts present are so small that relatively small contributions or losses appear important if treated in terms of percentage of change. It is best in these cases to deal mainly in absolute changes, and even then the difficulties of sampling and analysis introduce uncertainties.

The most common minor constituent shown in the analyses is titanium oxide. Basic rocks contain this oxide in greatest amount, but no consistent change during hydrothermal alteration is indicated. Acid rocks

which show small amounts also show no characteristic changes. In intermediate types there seems to be little change except during extreme silicification, as for example in the andesite at Bonanza, Colorado, which shows 1.30 per cent TiO_2 in the fresh rock and only .25 per cent in the highly silicified equivalent. At Juneau, Alaska, diorite shows .81 per cent TiO_2 in the fresh rock and .13 per cent in the albitized rock.

A gain in sulphur is characteristic of hydrothermally altered rocks, but this change is usually taken for granted, and attempts to treat it quantitatively are surprisingly few among the available analyses. In most analyses it is treated as iron disulphide (pyrite). The available data on gains in iron sulphide are summarized under pyritization.

Sulphates are known to form during hydrothermal alteration, particularly at shallow depths. Quantitative data, however, seem lacking. Review of mineral descriptions reveals alunite as the only distinctive sulphate of hydrothermally altered igneous rocks.

Gypsum forms but plays no important role in most deposits. Other sulphates probably occur but are apparently not distinctive and certainly are not abundant.

Other chemical constituents which occasionally appear in important amounts in the 80 analyses of altered rocks which were studied include MnO, P_2O_5, Cu_2S, CuO, BaO, PbS, ZnS, FeAsS, CaF_2, and CuFeS. The greisens show relatively important amounts of SnO_2, Li_2O, MoS_2, and fluorine. In some analyses lead, copper, zinc, arsenic, sulphur, and other elements may be expressed as percentage of the element but these are not common.

CHEMICAL CHANGES IN ORE DEPOSITS

Composite diagrams were plotted of many of the available analyses grouped according to Lindgren's (1933, p. 212) classification of ore deposits. These indicate the general chemical characteristics of the changes in the wall rocks of the various types.

Eight pairs of analyses of rocks altered near hypothermal veins were plotted. Not much change in silica and alumina was indicated. Ferric and ferrous iron increased in some rocks but more commonly decreased. Magnesia usually decreased and lime decreased, except in two cases. All but one occurrence showed a loss of combined water. This loss of water is somewhat characteristic of hypothermal deposits as might be expected from their relatively high temperature of formation. Of course if the so-called fresh rocks were free from alteration the water content would be very low, and a loss due to hydrothermal alteration would be practically impossible.

The most consistent changes are indicated by rocks of intermediate

composition altered in the mesothermal zone. Silica and alumina show relatively small changes, and ferric and ferrous oxide, magnesia, lime, and soda with rare exceptions show a decided loss. Potash, iron sulphide, and combined water usually show large relative gains.

Ten wall rocks of epithermal veins show little change in silica and alumina. Ferric and ferrous iron, magnesia, lime, and soda are, as a rule, decreased. Potash shows an equal number of gains and losses, and water usually shows a gain.

SUMMARY

Igneous rocks are variously affected by hydrothermal alteration. Softening and bleaching are common effects, but such processes as silicification and albitization may result in a freshened appearance. When the rocks are exposed at the surface, red and brown colors are commonly developed by oxidation of pyrite or other minerals.

Volume changes are normally not extensive, but in most cases some porosity results with an accompanying decrease in the bulk density of the rock.

The most important minerals developed in igneous rocks during hydrothermal alteration are quartz, sericite, chlorite, epidote, carbonates, and pyrite. Less common and abundant but locally important are alunite, kaolinite, adularia, biotite, serpentine, albite, tourmaline, fluorite, and many sulphides. Minerals particularly distinctive of hydrothermal alteration include sericite, alunite, adularia, fluorite, chlorite, and epidote.

The average of the fresh igneous rocks used in this study does not differ radically from Clarke's (1924, p. 29) average igneous rock. Average altered igneous rock and also average acidic, intermediate, and basic rocks indicate the net changes (Fig. 4). The average of all analyses of hydrothermal alteration shows a small net loss in silica and alumina, a somewhat greater loss of ferric and ferrous iron, and a relatively large loss of magnesia, lime, and soda. Potash and combined water show a net gain. Consideration of the average or net results alone is misleading. Good examples of hydrothermal alteration of igneous rocks are available which show relative gains for each important oxide, and equally good examples show losses for the same constituents. Therefore too great stress should not be laid on such generalizations as the tendency for potash to increase during hydrothermal alteration. Examples where potash decreases are important enough to deserve consideration, and a somewhat similar statement may be made for each oxide.

The review of data which are the basis for this paper reveals certain deficiencies in information on hydrothermal alteration of igneous rock: (1) Much more information on volume changes is desirable. Both bulk

and powder density determinations should accompany all analyses. (2) There are surprisingly few good examples of analyses of fresh and hydrothermally altered basic (*i.e.*, less than 52 per cent silica) rocks. Geologists finding good examples of altered basic rocks in the field would contribute to our knowledge of chemical changes in hydrothermal alteration to an important extent by carefully sampling both the fresh and altered rock and submitting them to analysis. (3) More calculations of mineral compositions of both fresh and altered rocks based on combined chemical and microscopic data are desirable. It is the writer's view that much of the value is lost if this is not done by the original investigator.

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MOVEMENT OF SOME GREENLAND GLACIERS

BY WILLIAM S. CARLSON

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ABSTRACT

The fourth Greenland Expedition of the University of Michigan was carried out in the winter of 1930-1931 within the Upernivik District of west Greenland.

Although the objectives of the expedition were primarily meteorological and aerological, glacial studies were also made. Attention was paid to the position of the ice front by means of triangulations. The front of the Upernivik Glacier was mapped in its entirety; extensive studies were made concerning its rate of movement, and these are compared with studies of movement made by Captain Ryder in 1886 and 1887. The positions of the fronts of Giesecke, Ussing, and Cornell glaciers were also determined.

It was found that the highest rates of motion were naturally encountered in the glaciers of the large icefjords. The greatest movements were found near the center of the ice stream. A comparison of Ryder's observations with the author's shows some agreement as well as some differences. No such great velocities as were found by Ryder in 1886 were recorded for the 1931 period. The direction of movement has remained the same. Of the many outlet glaciers in the district, Upernivik Glacier is by far the largest and most productive. Some of the glaciers in the district showed a marked retreat within the past 40 years. This retreat was greatest at the Upernivik Glacier near the south margin of the district.

INTRODUCTION

The fourth Greenland Expedition of the University of Michigan was carried out in the winter of 1930–1931 within the Upernivik District of west Greenland (Fig. 1).

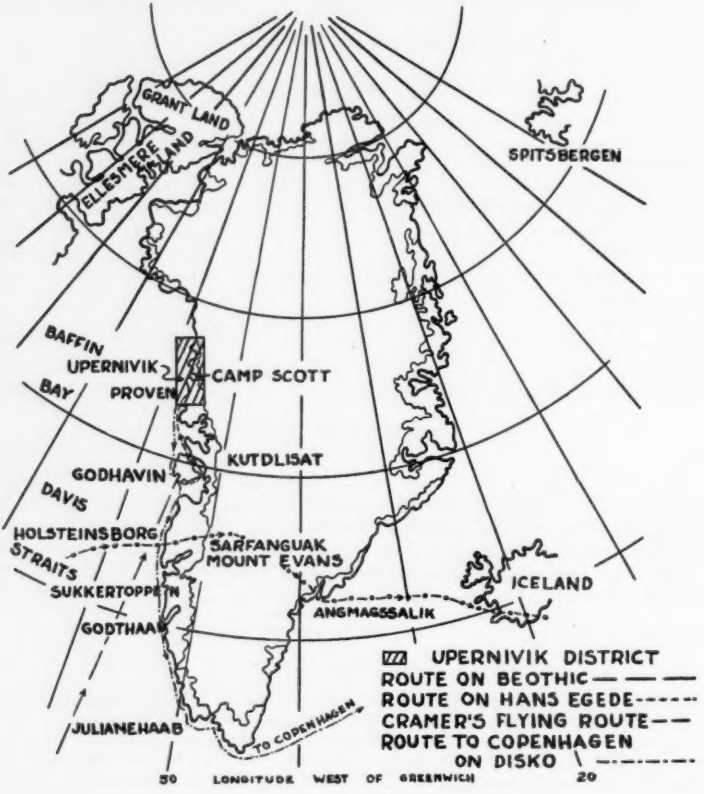

FIGURE 1.—*Map of Greenland*
Showing location of Camp Scott in Upernivik District.

Although the objectives of the expedition were primarily meteorological and aerological other scientific studies were made. In order to further glacial studies the author in February and March 1931, in the company of two natives, made a sledge journey from Camp I. D. Scott to Alison Bay and return (Fig. 2). Particular attention was paid to the position of the ice front by means of instrumental triangulation, supplemented

FIGURE 2.—*Outline map of Upernivik District in west Greenland*
(After official map of the Danish Government.)

by a number of photographs. During the winter and spring, the front of the Upernivik Glacier was mapped in its entirety; in addition, extensive studies were made concerning its rate of movement.

Along the entire stretch from the southern extremity of the district to

Alison Bay there are at least 14 outlets of the continental ice sheet into fjords, which constitute nearly one-fifth of the ice front. Of these outlet glaciers the Upernivik and Giesecke have been rated as the only ones of importance in iceberg production. As a result of the author's studies it seems that the Cornell Glacier is also important.

At the southern border of the district the ice is retained far inland by the high and large land masses. At Upernivik Icefjord it comes farther out and in the northern part of the district entirely covers the land forms of the coast. Following the inland ice north from Upernivik Glacier one finds that the elevation of the ice edge decreases and that the height of the bergs detached farther north is considerably lower.

The district is noted for its scarcity of mountain glaciers and highland ice, probably as a result of low precipitation. Several such glaciers were investigated on Nugssuak Peninsula. However, others may have been missed, for a thorough glaciological study is impossible during a hurried sledge journey, because in most part it must be undertaken when the region is still covered with snow.

UPERNIVIK GLACIER

Of the many outlet glaciers in the district, Upernivik Glacier is by far the largest and most productive. It extends from Nakitaisok on the south to Kagsserssuak on the north (Fig. 2), a distance of 15 miles. The greatest altitudes of the land—*i.e.* 3000–3300 feet—occur directly south and north of the glacier, whereas the islands and intermediate land masses adjacent to the glacier are much lower, seldom exceeding 700–800 feet above sea level.

The lower portion of the glacier, especially in the vicinity of Umanak, lies below the 500-foot contour. From the course of this contour it is evident that Upernivik Glacier continues as a curved depression into the inland ice. This is further substantiated by the line of maximum crevasses.

The sections of Upernivik Glacier south of Umanak and reaching to Nakitaisok and that between Hobbs Nunatak and Kagsserssuak do not appear to be active and present no new features of interest. They apparently are not active outlet glaciers but have more the characteristics of inland ice that is bounded by the sea. This impression is intensified when one is traveling on the glacier; the ice is almost completely free from crevasses and is covered with numerous thaw-water stream channels.

The middle portion of the glacier lies between Umanak on the south and Hobbs Nunatak on the north and is interrupted only by several small nunataks. The southern half of this stretch is greatly crevassed; the crevassed zone corresponds to the zone of greatest movement. The

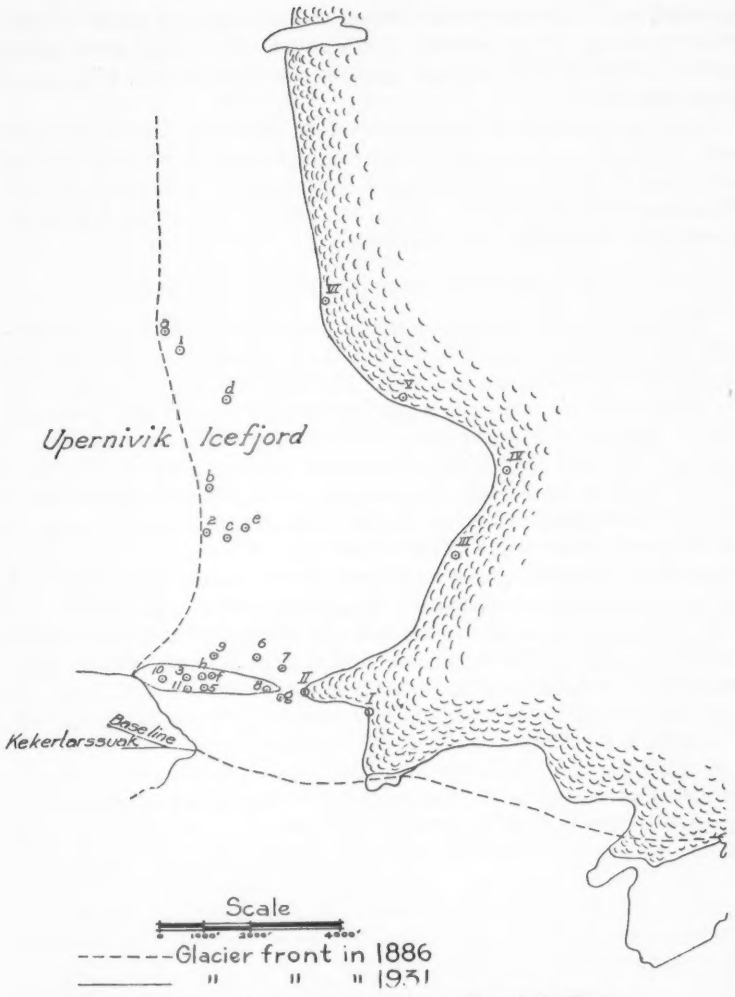

FIGURE 3.—*Map of active portion of Upernivik Glacier*

crevassed or active zone of the glacier is fronted by a lane of icebergs so continuous that the boundary between the glacier and the bergs is difficult to ascertain except when one is looking down from an elevation. The glacier front is flush with the margin of the inland ice, but the iceberg bank extends at least 2 miles into the fjord. Some of the bergs reach

as much as 150 feet above the surface of the water, and many of them have grounded. It is probable that many of these bergs have turned turtle inasmuch as the exposed portions are often covered with gravel and rock debris.

At all seasons there are strong currents in the waters around the bergs, which are driven out to sea rapidly, accomplishing an immense amount of erosion along the north shores of Kekertarssuak. Throughout the year the bergs were in constant motion, and even in mid-winter it was impossible to walk across the field of ice.

RYDER'S STUDIES OF UPERNIVIK GLACIER

In 1812 Giesecke (1910, p. 65), who was primarily interested in mineralogy, mentioned Upernivik Glacier, but it was not until 1886 that any systematic observations were made. In that year Captain Ryder (1889, p. 215–220) made observations to determine the height and movement of the glacier. His expedition visited the glacier on two occasions, in August 1886 and April 1887. From their camping place on Kekertarssuak, which at its eastern extremity was connected with the inland ice mass, they triangulated on the glacier. The August and April observations lasted over a period of 24 hours each.

A short summary of Ryder's data on the actual ice movement is given here for later comparison. Ryder measured a base line 1316 feet in length taken at an elevation of 358 feet above sea level. The stations or points measured are designated on Figure 3. The results of his observations of the ice movement are contained in Tables 1 and 2, Table 1 for the 12th to the 14th of August, 1886, and Table 2 for the period from the 20th to the 22nd of April, 1887.

TABLE 1.—*Ice movement according to Ryder's observations in August 1886*

Point	Average distance in 24 hours (Feet)	Distance from base line (Feet)	Height of ice front (Feet)
a	21.5	18344	146
b	64.4	11794	277
c	102.2	9380	360
d	37.7	15906	
e	56.4	9780	
f	4.6	3298	
g	6.5	3540	
h	7.1	3114	

TABLE 2.—*Ice movement according to Ryder's observations in April 1887*

Point	Distance in 24 hours (Feet)	Distance from base line (Feet)	Height of ice front (Feet)	Directions
1		17848	186.0	
2	33.8	9432	313.6	N 75 W
3	7.7	3058	285.0	N 77 W
4	8.2	3359	344.8	N 80 W
5	4.4	2782	309.5	N 78 W
6	6.3	5276	416.7	N 61 W
7	7.7	6216	404.1	N 78 W
8	5.2	5395	405.5	N 86 W
9	3.5	5485	406.1	N 70 W
10	7.4	2814		S 66 W
11	4.4	1950		S 68 W

The greatest rate of motion was near the center of point *c* (Table 1), the average movement was 102.2 feet per day, and in the period from the 13th to the 14th even reached 124.2 feet, a figure which surpassed all velocities of glaciers observed up to that time. This velocity decreases toward the side of the ice stream. Northward from the point *c*, the velocity decreases toward the side as shown by the velocities of 64.4, 37.7, 21.5 feet per day for the points *b*, *d*, and *a* respectively. From the south the points *f* to *h* show a similar but much greater reduction in velocity, the figures being from 7.1 to 4.6 feet for 24 hours. This is in part accounted for by the fact that they are also much nearer the rocks where the movement is always less. One sees, moreover, that the movement is variable for any given point. Comparing the points *c* and *e* which move in nearly the same direction but are separated by a distance of about 1700 feet, the first has an average velocity of 102.2 feet per 24 hours; the second has only 56.4 feet.

The points *a*, *b*, and *c*, situated on the front edge of the glacier, have heights of 146, 277, and 360 feet, respectively. From this it appears that the edge of the glacier has a greater height where the movement is the greatest.

In examining now the movement in April (Table 2), it is immediately evident that this, at least during the days when the observations were made, was very much slower.

Point *1* thus was not in motion in April, although it is located near the point *a* which in August had an average velocity of 21.5 feet per day. In April point *2* had an average velocity of 33.8 feet per 24 hours, whereas

the corresponding point *c* of the summer observations had an average velocity of 102.2 feet per day. All the other points had an average velocity from 3.5 to 8.2 feet, but they were all found near the island of Kekertarssuak.

Ryder found the movement to be generally WNW except for the points *10* and *11* which move WSW.

The elevations of points *1* and *2* near the edge of glacier were 186.0 and 313.6 feet respectively above sea level. These show some fluctuations from the summer heights, although elevations are highest where the velocity is the greatest.

Thus from Ryder's observations it is seen that the ice movement is greatest near the center of the ice stream, that the summer movement is greater than the winter, and that the height of the ice precipice is greater where the largest velocity is found.

OTHER EARLIER STUDIES

Other studies of glacial movement in Greenland, which, however, were not checked by the author, do not show the great velocity found by Ryder in August 1886. In the most famous of Greenland glaciers—that of Jacobshavn—Helland (1876) in 1875 determined the rate of motion to be little less than 65.6 feet within the 24 hours. A single determination by Engell (1904, p. 43) on the same glacier in 1902 indicated 74.8 feet per day.

In the western glacier of North Sermilik (South Greenland) Moltke and Jessen (1896, p. 99) found a similar maximum rate of motion—about 65 feet per day.

The measurements of Steenstrup (1883, p. 83) indicated that the large glaciers did not move at a much slower rate in spring than in summer. In substantiation of this the following values may be cited: In Itivdliarssuk, Steenstrup, at the beginning of April, found a maximum rate of motion of 46 feet per day. In July, Von Drygalski (1892, p. 259–267) found a maximum rate of motion of 53.4 feet per day, or practically the same. According to Drygalski's determinations of the rate of motion of the great Karajak, the rate was the same for summer and winter, with the highest rate about 65 feet per day. Further, the rate of motion within the surface proved to increase toward the end of the glacier.

STUDIES IN 1931

In April 1931 the author undertook a number of measurements of the movement of the ice. They were taken in two series and were designed to study horizontal motion as well as vertical fluctuations. The data on

the vertical variation which were measured along the lateral wall of the glacier have not yet been analyzed.

Ryder's base line on Kekertarssuak was virtually remeasured, the length obtained being 1266 feet. From this six easily recognizable points

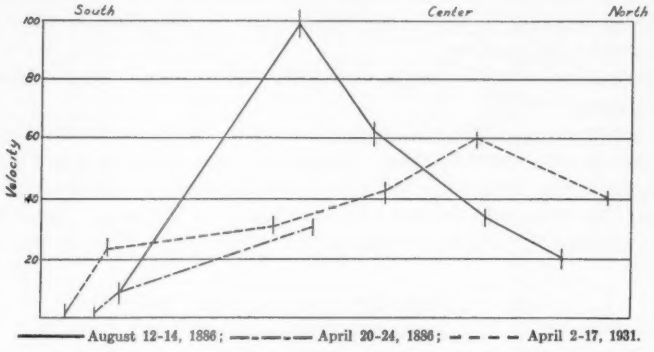

FIGURE 4.—*Plot of velocities, Upernivik Glacier*
Illustrating decrease in ice movement from center toward sides.

on the ice were chosen. The points selected averaged between 1000 and 1500 feet from the glacier's edge and were spaced at distances of approximately 2000 feet. The measurements of these points began on April 2 and were made once every 24 hours through April 9. Because of bad weather the work was discontinued for 2 days but was again resumed on the 12th and brought to a close on April 17. Thus, the observations lasted over a period of 15 days with one interruption of 2 days. The results of the observations are found in Table 3.

It will be seen from Figure 3 that stations I and II are located near the south margin of the glacier, and that stations III, IV, and V are near the middle. Station VI approaches the northern boundary of the glacier.

A comparison of these stations shows that the greatest velocity is near the center of the ice stream at point V, which had an average movement of 59.77 feet per day, and on the 5th even reached 67.44 feet— the maximum velocity shown by any station. The velocity decreases toward the sides. Northward from point V the speed decreases toward the side as shown by point VI which has an average daily movement of 40.32 feet. As one approaches the south side of the glacier from the center, stations IV, III, II, and I show a similar reduction in velocity, the figures being 43.52, 32.8, 26.11, and 2.6 feet respectively. This decrease in velocity toward the sides of the glacier becomes more evident by an examination of Figure 4.

Figure 5 is a plot of each daily velocity. Points I, II, and VI show remarkable consistency over the entire period, points III and VI indicating a slight increase in movement as they approach the edge. Station I overlies a partially covered nunatak and shows practically no variations in movement. Stations II and IV are remarkable in that both show a sudden increase in movement that cannot be coordinated with any temperature fluctuations.

The movement was found to be WNW and W except for the point I which moved WSW.

A comparison of Ryder's observations with the author's shows some agreement and some differences. Figure 4 shows the decrease in velocity from the center toward the sides that was indicated by all observations made. No such great velocities as were found by Ryder in August 1886 were recorded for the April 1931 period. The April 1887 observations

TABLE 3.—*Observations on ice movement, April 1931*

(Movement given in feet)

Point	I	II	III	IV	V	VI
Date						
2	.....	.....	.....	.....	.....	.....
3	X	7.21	20.1	.....	46.09	38.04
4	X	11.21	23.4	22.20	46.09	38.77
5	X	10.44	24.22	21.38	67.44	37.87
6	10.1*	12.24	25.8	22.14	65.95	36.72
7	X	10.77	30.2	44.44	67.06	39.02
8	X	10.29	29.4	44.20	65.12	39.26
9	X	18.79	33.7	43.57	64.04	37.38
10	X	X	X	X	X	X
11	X	X	X	X	X	X
12	14.6†	46.53**	97.6**	130.4**	167.30**	117.5**
13	X	36.06	38.6	43.19	62.20	38.51
14	X	53.42	38.8	43.28	61.85	43.61
15	X	64.92	42.2	65.05	59.55	44.64
16	X	51.66	44.2	65.05	64.31	47.04
17	14.3††	58.14	43.8	64.39	58.83	46.53
Total movement	39.0	391.68	492.2	609.29	896.59	604.89
Average daily movement	2.6	26.11	32.8	43.52	59.77	40.32
Direction of movement	S 73 W	N 77 W	N 64 W	N 72 W	N 75 W	N 85 W

X No observation made.
* Total movement from 2nd to 6th.
† Total movement from 6th to 12th.
** Total movement from 9th to 12th.
‡ Total movement from 12th to 17th.

conform generally with the ones made in April 1931, though the former are not complete enough for a definite comparison. All stations located near Kekertarssuak show a very small movement.

The direction of movement in 1931 was approximately the same as in 1887.

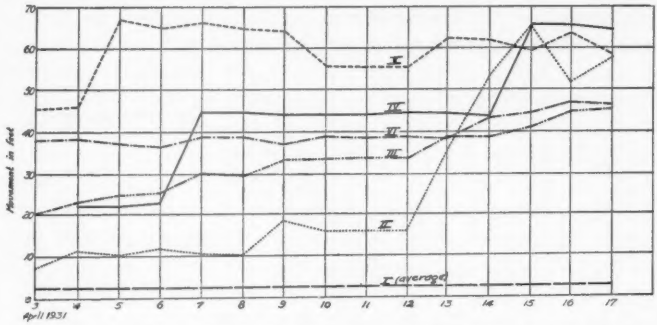

FIGURE 5.—*Plot of daily velocities, Upernivik Glacier, April 2-17, 1931*

The position of the ice front shows that since 1887 there has been a retirement that reaches 5000 feet in places but averages approximately 3000 feet along the active margin of the glacier.

GIESECKE'S GLACIER

Giesecke's Glacier (Fig. 6) may be called a quadruple glacier. Each part is separated by a partial nunatak, and its total sea frontage is more than 15.5 miles. The portion north of the island Nulok is stagnant. The ice surface is quite smooth, though local sags with moulins and snow-filled stream channels do occur, and along the eastern land margin are a few widely separated crevasses. Along the western land margin the surface is smooth, and an easy ascent can be made up the glacier.

The second portion of the glacier shows indications of being slightly more active. Although the surface is somewhat more crevassed, the production of icebergs still remains practically negligible.

The third or middle portion of the glacier is the one with the greatest output of ice. This part of the glacier may also be divided into a north and south section by a very small nunatak. As the latter was not mentioned by Ryder (1889, p. 243) who investigated the glacier, it, no doubt, has become visible since his studies were made. In Ryder's account it is the portion of the glacier which at that time overlay the nunatak and in 1886 lay close to the island of Anarusuk to the west. In former years the ice reached the island, forming in the interior a lake where seals were

caught in the springtime. This barrier has now retreated approximately 3200 feet from Anarusuk, and the resulting embayment is called Tasingortok (that which becomes a lake) by the natives. Insofar as can be

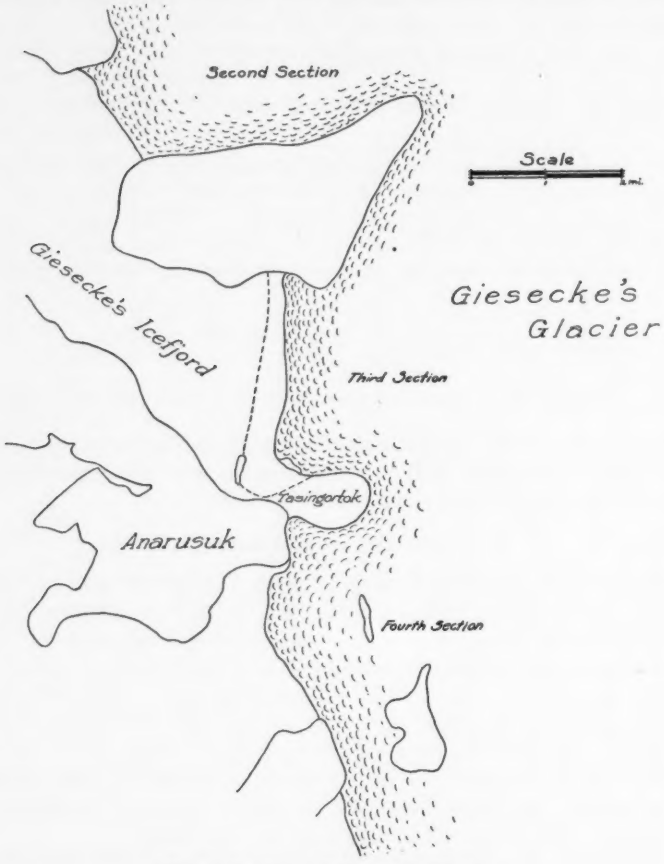

FIGURE 6.—*Map of Giesecke's Glacier*

determined from the existing maps this active part of the glacier has retired about 2000 feet since 1886.

The northern arm of the middle or third section of the glacier is about 4.5 miles wide. This section of the glacier is the most active, and it is estimated by the writer to yield about 90 per cent of all the ice in Giesecke Icefjord. Along the entire 4.5 miles the sea wall is a perpendicular cliff

of ice varying in height between 100 and 200 feet. The surface is remarkably broken by transverse crevasses except for the portion overriding the dividing nunatak where the surface of the ice is smooth but hummocky. The ice does not rise in mounds but slopes gently west-southwest from the interior at approximately 2 degrees. The division south of the small nunatak furnishes the remainder of the bergs. Along the sea margin of this section the glacier rises either as a steep slope or as a wall of ice. The surface is greatly broken by the general system of transverse crevasses.

A partial nunatak separates this active section of the glacier from another which terminates in the fjord south of Anarusuk. This new outlet, in want of a proper name, will be called the fourth section of Giesecke Glacier.

It was found that the ice between the third and fourth sections of the glacier, with one exception, sloped moderately toward the separating nunatak, permitting frequent easy ascents and descents. Along the eastern land margin the ice impinges forcibly against the base of the nunatak, but near the terminus of the fourth arm there is a trench formed between Anarusuk and the ice. The trench ends in a small moat bounded on one side by a moraine and on the other by the steep slope of the glacier. The bottom of the trench and moat was filled with a soft, drifted snow. The marginal moraine responsible for the moat curves in an arc extending for about 100 feet along the face of the glacier. The moraine is composed of loose boulder clay containing small pieces of gneiss, porphyritic red granite, and fragments of basalt.

The fourth section of the glacier front is about 3 miles wide. The entire front is a wall of ice not more than 150 feet high and in some places was carrying no debris in the upper portion at the time of observation. Though the surface is crevassed, except that portion immediately adjoining Anarusuk to the north, the movement is not very rapid, for the amount of ice coming from the front was small. There were no large bergs in the fjord, and the fringe of broken ice that has fallen from the cliff extends less than 300 feet beyond the face of the glacier.

About a mile from the southern land of the fourth section of the glacier margin two nunataks rise at least 1000 feet above the surface of the ice. These nunataks are separated by a narrow strip of ice that looks like a hanging glacier whose source, of course, is the inland ice east of the nunataks. Here and there are mounds of ice that are cracked radially. To the north of the large nunataks a nunatak is just beginning to protrude through one of these prominent mounds.

The iceberg production of Giesecke's Glacier in comparison with that of Upernivik Glacier has long been a matter for discussion. Too much

importance has been placed upon the amount of ice produced by the former. The conclusion is drawn from observations, from information obtained from intelligent natives who are acquainted with conditions throughout the year, and from Dr. Rask who, on several occasions during the summer season, has visited the fjord within which the glacier terminates.

Ryder (1889, p. 235–236) wrote that in 1886, according to Greenlander information, the fjord, which measured 40 miles from Tugtokortok and Agparsuit to the productive part of the glacier, carried so much ice that the ice extended from 4.5 to 5.0 miles from the front of the glacier; this does not take into account that the sea around Saitok was always full of less compact ice. Since that time conditions have changed entirely. At present several bergs are found in the passage near Nulok, still fewer around Saitok, and only a few along the north shore of the fjord near its source. The extent of the closely packed icebergs does not go farther than a mile beyond the front of the productive portion of the glacier. From this it is concluded that Giesecke Glacier is only slightly more active than Cornell Glacier, though the latter is seldom mentioned as an ice producer.

USSING GLACIER

Ussing Glacier is in two parts divided by a partial nunatak near the southern land margin. The width of the northern arm is about 2⅗ miles, while that of the southern arm is about a mile. The sea front is a continuous cliff of ice varying from 100 to 125 feet in height. Because of the deep snow everywhere bordering the glacier no attempt was made to attain the land margin beyond sea level. Viewed from a distance of less than a mile, wherever the glacier impinged upon the land it presented neither a steep slope nor a vertical wall of ice. On the land margin near sea level where closer inspection was possible, the ice slope was faced by a low moraine. The morainic material was heavy boulder clay composed mainly of granitic gneiss, but it also contained quartzite and garnetiferous granite. Between the nunatak which divides Ussing Glacier and the northern land margin the ice rises in several circular mounds perhaps 900 to 1200 feet in diameter and greatly crevassed radially. One of these mounds is especially prominent and leads one to believe that they are caused by subglacial topographic elevations. The same feature was seen on Cornell Glacier farther north and on Giesecke Glacier. Bordering the northern land margin is a strip of ice about 1500 feet wide that is entirely without surface irregularities and would permit easy access toward the interior.

Lack of time and the roughness of the ice in front made it inadvisable

and impractical to determine accurately the rate of movement of the glacier. However, in consideration of the few small bergs and the general scarcity of smaller ice in the fjord at the front of the glacier, the movement is evidently very slow—much slower than that of Cornell Glacier.

The direction of movement of the glacier, judged from the position of moraines and crevasse systems, is to the southwest on the side north of the nunatak and to the northwest south of the same nunatak. The partial nunataks or land masses north and south of the glacier deflect the movement in a direction diagonal to that of the inland ice.

About 3 miles east of this dividing nunatak is another which rises only a few hundred feet above the surface of the ice. No medial moraines were observed, but any superglacial features that may exist would be obscured by the heavy blanket of snow that covers everything during the sledging season. Evidence of glacial retirement was to be seen, but the amount could not be determined because of lack of any previous information about the position of the front.

CORNELL GLACIER

Cornell Glacier, like Ussing Glacier, is a double one divided near the northern boundary by a partial nunatak named Mount Hope. The sea frontage totals 6 miles, of which 1½ are north of Mount Hope. The glacier is slightly active along the entire 6 miles. Tarr (1897, p. 251), who studied the glacier in 1896, did not endeavor to determine the rate of movement but merely confined himself to the opinion that, judging from the amount of ice coming from the front, it was not very rapid. At present the movement may be considered as moderate, being rated as third in importance of production in the Upernivik District. It is exceeded by Upernivik Glacier, which is without doubt the most productive, and Giesecke Glacier. According to Greenlander information bergs breaking from the glacier front are so large that at times during the winter season the sea ice for miles around is broken. Three days after leaving that vicinity the writer was informed that such a large section had broken from the glacier front that the sea ice as far as Itivsalik, 20 miles away, was made unsafe for sledging. No bergs of such huge dimensions were noticed by the writer previous to this great discharge. They were smaller, especially as regards height, than those seen farther south. However, the discharged bergs in Ryder's Isefjord were fairly close together as far as 6 miles from the most productive part of the glacier. The roughness of the sea ice because of broken ice from the ice cliff made sledge travel almost impossible within a lane about a mile in breadth bordering portions of the ice terminus. No moraines were visible on the surface of

the glacier, but a lateral moraine is at present being deposited on the southern land margin. The nunatak described by Tarr as just becoming visible in 1896 may be slightly more prominent, but the writer was able to determine no appreciable change in the front during the past 40 years.

GLACIAL RETIREMENT

Glacial retirement has been studied previously in some detail only on one Greenland glacier—that of Jakobshavn. The position of the front was measured several times between Rink's (1889, p. 273) visit in 1851 and that of Engell (1904, p. 58) in 1902. Although there were short periods of advance, they were exceeded by a retirement which totalled 6.8 miles by 1902. Other glaciers in the neighborhood, according to Von Drygalski, also bear distinct traces of retreat.

Koch (1928, p. 191–464), basing his judgment upon direct observations, reports of other expeditions, and reports of Eskimos transmitted from earlier generations, writes that the edge of the Inland Ice in North Greenland has not changed appreciably from the present position during the last 100 years at least. Koch has contributed much material on the movements of the front of outlet glaciers in North Greenland. He describes 15 advancing glaciers, 8 stationary glaciers, and 9 retreating glaciers. A few glaciers show oscillations of advance and retreat of varying duration and extent. He mentions especially Brother John Glacier and the several glaciers in the Cape York District.

De Quervain (1920, p. 269) found the accumulation of ice to be greater than the observed dissipation, which seems to indicate that the glacier is fully maintaining itself in its present extent. As for coastal glaciers, De Quervain writes that in 1912 the fronts seemed to be generally receding. Three glaciers of Blaesdal, Disko Island, were found to have retreated during the preceding 15 years.

Conflicting reports from natives indicate that the ice in some places has had a different distribution from the one it has now. Thus Holm (1883, p. 171) writes an account of a south Greenland glacier that had advanced so rapidly that within living memory it had buried a group of Norse ruins. Similar reports of advance are also mentioned by Ryder (1889, p. 237) from Umanak District and Jensen (1889, p. 33) from the Sukkertoppen District. On the other hand according to other reports the ice is retreating.

CONCLUSIONS

It was found that the highest rates of motion were naturally encountered in the glaciers of the large icefjords, their productivity being due to their rapid advance in connection with their great thickness. The greatest

movements were found near the center of the ice streams. Going from the south toward the north the writer found that the ice front ends in steep walls especially along the sea margin, but there was a notable decrease in elevation. Within limited areas a certain uniformity can at times be traced as regards the changes of the position of the ice margin. Some of the glaciers in the district showed a marked retreat within the past 40 years. This retreat was greatest at the Upernivik Glacier near the southern margin of the district. The few valley glaciers noted were also in a state of retirement.

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GEOPHYSICAL INVESTIGATIONS IN THE EMERGED AND SUBMERGED ATLANTIC COASTAL PLAIN

PART III: BARNEGAT BAY, NEW JERSEY, SECTION

BY MAURICE EWING, GEORGE P. WOOLLARD, AND A. C. VINE

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ABSTRACT

Seismic refraction measurements, from Princeton to Barnegat Bay, New Jersey, have been made as a continuation of similar measurements of the depth of the crystalline basement made at Cape Henry, Virginia, and Woods Hole, Massachusetts, in 1935. The standard technique for seismic refraction measurements was followed. The observed depths are in agreement with the well logs of two deep wells extending to the basement. A geologic section constructed from these measurements is in agreement with known geologic and gravitational data.

FOREWORD

In order to avoid the repetition of data and diagrams the writers present the following seismic investigation of the sub-surface structural conditions in the Coastal Plain of New Jersey as one composite paper, covering both the seismic investigation and the geological significance of the results.

The geologic interpretations are the work of Woollard, and Ewing is responsible for the new method used for several of the travel-time curves. All the writers collaborated in conducting the field work, in reducing the data, and in preparation of the report.

INTRODUCTION

The writers present a third seismic refraction profile in the study of the fundamental structural conditions along the Continental Shelf. The section presented begins near Princeton, New Jersey, and ends at Silverton, New Jersey, on Barnegat Bay. Eight land seismic stations were established with a station interval of about 5 to 6 miles. Of these, two stations, Charleston Springs and Lakewood, had reverse profiles run because the single profiles at these stations had indicated the need of further measurements. At both stations a slight slope was observed for the basement rocks which was in agreement with the slope estimated by less detailed measurements at the other stations. The seismic results were verified by all the well log data which were available along the section.

The method of conducting the seismic survey was the same as that described for land stations in Part I (Ewing, Crary and Rutherford, 1936, p. 759) with the exception of the stations at Hightstown, Charleston Springs, and Lakewood. At these stations a method of analysis was applied which the writers believe has not previously appeared in published form. This method will be described in detail in the discussion of the stations.

In addition to the information concerning the configuration of the basement rocks it was found that certain geologic horizons in the over-

lying sediments could be traced accurately, as was proved by subsequent well data. It also appears that the basement rocks underlying the Coastal Plain can be differentiated by geophysical measurements.

ACKNOWLEDGMENTS

The writers would like to acknowledge the splendid spirit of cooperation and the help extended to them by Meredith E. Johnson, New Jersey State Geologist, and the New Jersey State Geological Survey of the Department of Conservation. Much of the success of this project can be attributed directly to this office, since practically all of the well and bore hole data utilized are on record only in its files. To this office the writers are also indebted for financial assistance in carrying out the project. To H. C. Barksdale of the United States Geological Survey and the New Jersey State Water Policy Commission the writers are indebted for advice and the loan of equipment for sinking shot holes in difficult terrane.

For assistance in carrying out the field work the writers wish to acknowledge the help extended by J. L. Worzel, R. J. McCurdy and N. H. Webster of Lehigh University.

To the Geological Society of America the writers are indebted for the use of field equipment constructed from funds allocated for the carrying out of seismic investigations on the ocean floor.

Ewing and Woollard are indebted to the Guggenheim Foundation and to the American Geophysical Union, respectively, for Fellowships covering the period of these researches.

LOCATION OF SECTION

In establishing the line of the section two factors were considered. The line was chosen to be essentially perpendicular to the strike of the structure being investigated, and to permit the use of the maximum amount of geologic data as revealed by well logs. This latter factor was considered important because some geologists desired additional verification of the seismic results by well log data to supplement those previously obtained on the Cape Henry Section and at Matthews, Virginia. Accordingly, a section line was laid out essentially perpendicular to the regional structure and passing through Hightstown, New Jersey, where a well encounters basement at —375 feet, and through Jackson's Mills where a well indicates basement at —1226 feet.

In running the station profiles an effort was made to have their lines as nearly perpendicular to the section line as possible as this would be the direction of least slope of the basement. However, natural obstacles and

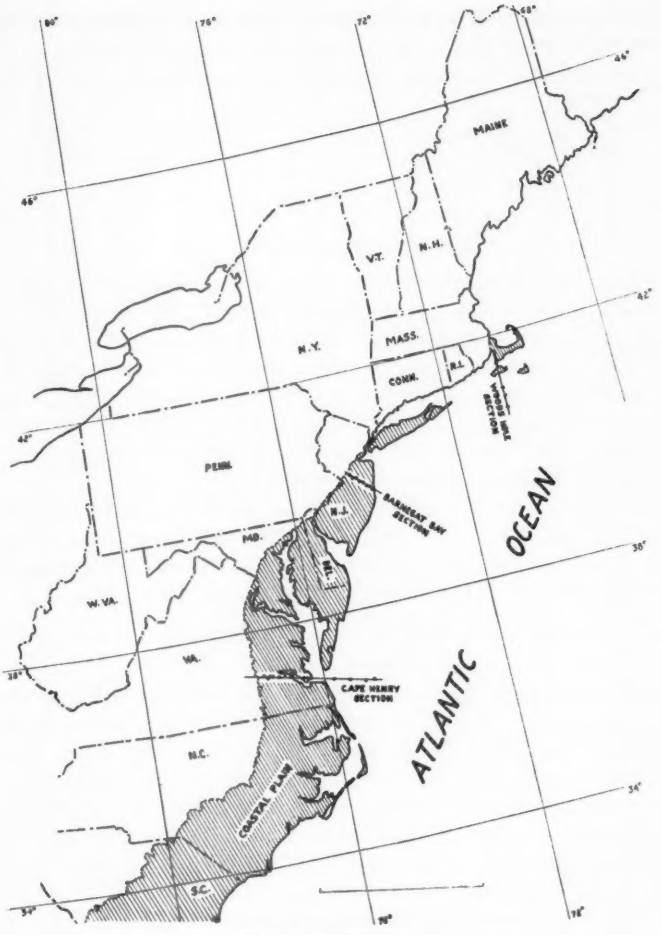

FIGURE 1.—*Key map*
Showing seismic sections in the Coastal Plain.

cultural conditions were frequently the deciding factors in running the individual station lines.

Figure 1 shows the relative position of the three seismic sections that have been established to date in this study of structural conditions along the continental border. Figure 12 indicates the location of the Barnegat Bay line in detail with the eight station profiles.

The following table gives the seismic stations established and the distances between them:

	Miles
Plainsboro	
Hightstown	5.2
Dis Brow's Hill	2.4
Charleston Springs	6.2
Jackson's Mills	4.0
Lakewood	4.9
Cedar Bridge	4.0
Silverton	5.2

METHOD OF INVESTIGATION

The method employed was the standard refraction method described in Part I (Ewing, Crary and Rutherford, 1936, p. 759) with a few instrumental changes. The geophones and amplifiers were of a new design built under a grant from the Penrose Fund, and were those used in refraction measurements on the floor of the ocean in September, 1937. Transceivers operating in the 5-meter band were tried out for the radio communication but these proved unreliable at distances greater than one mile, so use of long-wave equipment was resumed.

The records were interpreted by means of the standard method described on page 763 of Part I for all of the stations except those at Hightstown, Charleston Springs and Lakewood. At these stations the procedure discussed in the following section was used in analyzing the data.

REFRACTION FORMULAS FOR MULTIPLE LAYERS

GENERAL STATEMENT

At two stations in the Barnegat Bay section it was possible to distinguish four seismic "layers" in the geologic column, these layers being inclined at various angles to the horizontal. The literature contains formulas for calculations on any number of horizontal layers, but the writers have not found suitable published methods for treating more than three sloping layers. Von Schmidt (1931, p. 50) gave the original solution for the three layer problem, but its form is not convenient for extension to a greater number of layers. Neither the method of Part I nor that of Service (1934, p. 73) appears to be readily adaptable to the present problem. To meet this situation, a method was developed which is applicable to any number of sloping layers.

ASSUMPTIONS

The formula is derived on the basis of the following statements, which serve to define the problem and to summarize those facts about the seismic method which are assumed to be known to the reader:

(1) Each layer is bounded top and bottom by planes, and transmits seismic waves at a constant velocity.

(2) At the interface between two layers the path of the seismic wave is bent according to Snell's Law, $\sin \alpha_1 / \sin \alpha_2 = V_1 / V_2$.

(3) A wave travelling in any layer with velocity V, and incident upon

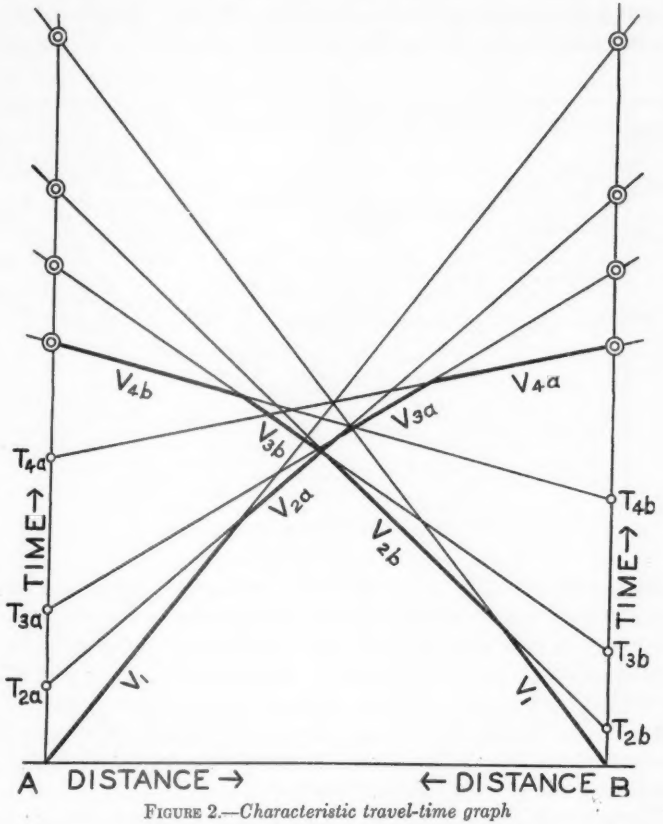

FIGURE 2.—*Characteristic travel-time graph*

the surface of the layer at an angle α with the normal, has an apparent velocity $V/\sin \alpha$ along the surface.

(4) Any travel-time will be unchanged if shot-point and recording-point are interchanged.

In cases where the actual conditions deviate slightly from these assumptions—where for instance an interface is not perfectly plane—the solution yields a plane which approximates or averages the actual surface. Deviations of actual from assumed conditions are revealed as departures of the

observed travel-time data from the set of straight lines drawn on the travel-time graph.

CHARACTERISTIC TRAVEL-TIME GRAPH

Figure 2 shows a characteristic travel-time graph for four sloping layers with velocities V_1, V_2, V_3, and V_4. It consists of a profile "a" from A to

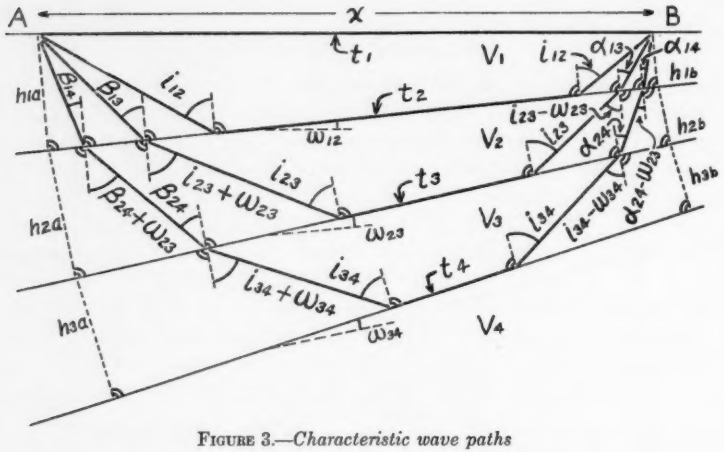

FIGURE 3.—*Characteristic wave paths*

B, and a reverse profile "b". Only those parts of the graph represented by heavy lines may be observed on the seismograms as first arrivals, but it is frequently possible to fill in certain other parts of the diagram by use of later arrivals. The circled points in Figure 2 are "reverse points" for the profiles "a" and "b". There is a pair of reverse points for each of the layers V_1, V_2, V_3, and V_4. It should be noted that each pair agrees with Assumption (4), which states that the travel-time from A to B shall be equal to that from B to A for any path.

The data which are taken from the travel-time graph are: (1) the time-intercepts T_{2a}, T_{2b}, T_{3a}, T_{3b}, T_{4a}, T_{4b}, and (2) the apparent velocities V_1, V_{2a}, V_{2b}, V_{3a}, V_{3b}, V_{4a}, V_{4b}. The velocities are obtained as the reciprocal slopes of the corresponding branches of the travel-time curve.

It will be apparent from the sections which follow that a third profile "c", on this same line and in the same direction for example as "a", must satisfy the two sets of conditions: (1) its reverse points must be equal to those of "b", and (2) its time-intercept points must be collinear with those of "a" and "b".

CHARACTERISTIC WAVE PATHS

Figure 3 shows the various paths by which the waves used in refraction measurements may travel between two points, A and B. Each angle ω represents the dip of a given interface with respect to the one above it, and the angles α, β, and i are defined by Figure 3. Let h be the perpendicular distance from A to the V_1V_2 interface; h_2 that from the foot of h_1 to the V_2V_3 interface; etc.

From Assumptions (2) and (3) it is seen that all angles may be determined from data taken from the travel-time curve by means of the following formulas:

$$\left.\begin{aligned}
&V_1/V_{2a} = \sin(i_{12} - \omega_{12});\ V_1/V_{2b} = \sin(i_{12} + \omega_{12});\\
&\qquad V_1/V_2 = \sin i_{12}.\\
&\text{---------}\\
&V_1/V_{3a} = \sin(\alpha_{13} - \omega_{12});\ V_1/V_{3b} = \sin(\beta_{13} + \omega_{12})\\
&V_1/V_2 = \sin\alpha_{13}/\sin(i_{23} - \omega_{23}) = \sin\beta_{13}/\sin(i_{23} + \omega_{23})\\
&\qquad V_2/V_3 = \sin i_{23}\\
&\text{---------}\\
&V_1/V_{4a} = \sin(\alpha_{14} - \omega_{12});\ V_1/V_{4b} = \sin(\beta_{14} + \omega_{12})\\
&V_1/V_2 = \sin\alpha_{14}/\sin(\alpha_{24} - \omega_{23}) = \sin\beta_{14}/\sin(\beta_{24} + \omega_{23})\\
&V_2/V_3 = \sin\alpha_{24}/\sin(i_{34} - \omega_{34}) = \sin\beta_{24}/\sin(i_{34} + \omega_{34})\\
&\qquad V_3/V_4 = \sin i_{34}.\\
&\text{---------}
\end{aligned}\right\} \quad (1)$$

DEPTH CALCULATIONS FROM TIME-INTERCEPTS

Consider the point B, in Figure 3 to be moved a short distance toward A. It is evident that all angles remain constant and that the travel-time for each path is represented by an equation of the form $t = x/V_a + T_a$, where T_a is the time-intercept of the value on the travel-time curve for $x = 0$. These time-intercepts do not represent actual travel-times, because each path ceases to exist as the path of a real wave when x is less than a certain value. They have a definite mathematical significance and are useful in the calculation of depth. Figure 4 represents these paths when x has been reduced to zero, and by comparing it with the preceding figure the following expressions for the time-intercepts are obtained:

$$\left.\begin{aligned}
T_{2a} &= (AC + AE)/V_1 - CE/V_2\\
T_{3a} &= (AF + AG)/V_1 + (FH + GJ)/V_2 - HJ/V_3\\
T_{4a} &= (AK + AL)/V_1 + (KM + LN)/V_2 +\\
&\qquad (MO + NQ)/V_3 - OQ/V_4
\end{aligned}\right\} \quad (2)$$

By the use of Figure 4 the time-intercept T_{2a} may be expressed in terms of measurable quantities through substitution in the above equation.

$$T_{2a} = 2h_1/(V_1 \cos i_{12}) - 2h_1 \tan i_{12}/V_2$$
$$= (2h_1/V_1 \cos i_{12})(1 - \sin^2 i_{12}) = 2h_1 \cos i_{12}/V_1.$$

The corresponding expression for T_{3a} is seen in Figure 5 to be

$$T_{3a} = (AF + AG)/V_1 + (FH + GJ)/V_2 - HJ/V_3.$$

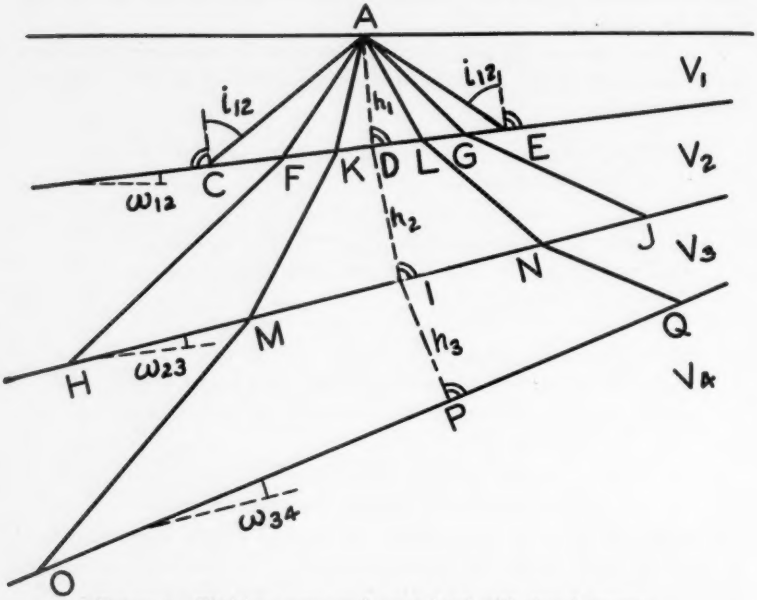

FIGURE 4.—*Fictitious wave paths associated with time-intercepts*

From Assumption (3) the apparent velocities along the V_1 V_2 interface are

$$V_2/\sin(i_{23} - \omega_{23}) = V_1/\sin \alpha_{13} \text{ and } V_2/\sin(i_{23} + \omega_{23}) = V_1/\sin \beta_{13}.$$

By using these apparent velocities the path $FH + GJ - HJ$ may be shifted to $DR + DS - RS$, the time for which is known to be

$$2h_2 \cos i_{23}/V_2$$

from the result of the preceding paragraph.

$$T_{3a} = 2h_2 \cos i_{23}/V_2 - FD \sin \alpha_{13}/V_1 - DG \sin \beta_{13}/V_1$$
$$+ (AF + AG)/V_1$$
$$= 2h_2 \cos i_{23}/V_2 - h_1 \tan \alpha_{13} \sin \alpha_{13}/V_1 - h_1 \tan \beta_{13} \sin \beta_{13}/V_1$$
$$+ h_1/(V_1 \cos \alpha_{13}) + h_1/(V_1 \cos \beta_{13})$$
$$= 2h_2 \cos i_{23}/V_2 + h_1(\cos \alpha_{13} + \cos \beta_{13})/V_1$$

The derivation may be extended to include any number of layers by the method of induction. Suppose the formula $T_{n-1,a}$ which is the solution for the case of $n - 1$ layers, has been obtained. Apply it directly to the layers V_2 to V_n, and then extend it to include the topmost layer by

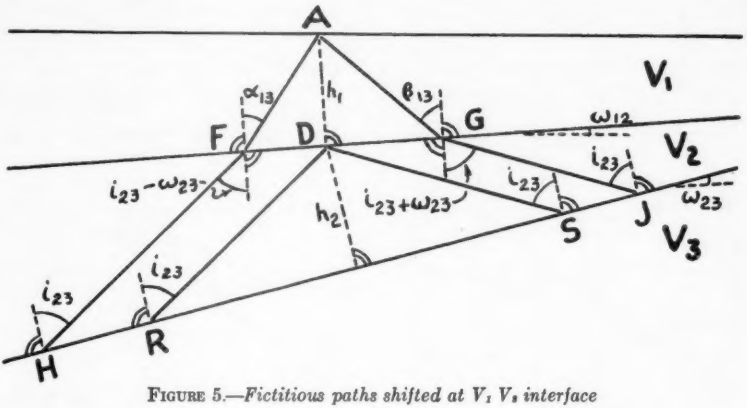

FIGURE 5.—*Fictitious paths shifted at V_1 V_2 interface*

the use of apparent velocities along the V_1V_2 interface as illustrated above. This operation will increase every subscript in the formula for $T_{n-1,a}$ by unity and will add to it the term $h_1 (\cos \alpha_{1n} + \cos \beta_{1n})/V_1$, giving the proper result for T_{na}. The resulting time-intercept formulas are:

$$\left.\begin{aligned} T_{2a} &= 2h_1 \cos i_{12}/V_1 \\ T_{3a} &= 2h_2 \cos i_{23}/V_2 + h_1(\cos \alpha_{13} + \cos \beta_{13})/V_1 \\ T_{4a} &= 2h_3 \cos i_{34}/V_3 + h_2(\cos \alpha_{24} + \cos \beta_{24})/V_2 \\ &\quad + h_1(\cos \alpha_{14} + \cos \beta_{14})/V_1 \end{aligned}\right\} \qquad (3)$$

Equations (1) and (3) permit determination of all the values h, ω, and V. They are the solution of the problem. The vertical depth to a given layer at point A, which is the quantity needed for checking against data from bore holes, may be calculated from the values of h and ω.

SLOPES TRANSVERSE TO PROFILES

The foregoing discussion contains no mention of slopes in the direction at right angles to the line of profile; these may be expected to occur to the same extent as slopes along this line. All slopes found to date in the Coastal Plain have been small, and in such cases the errors introduced into the values given for V, h, and ω will be small quantities of the second order. Slope transverse to the line of profile could be estimated at each

station by use of a profile normal to the existing one, but the additional work would not be justified.

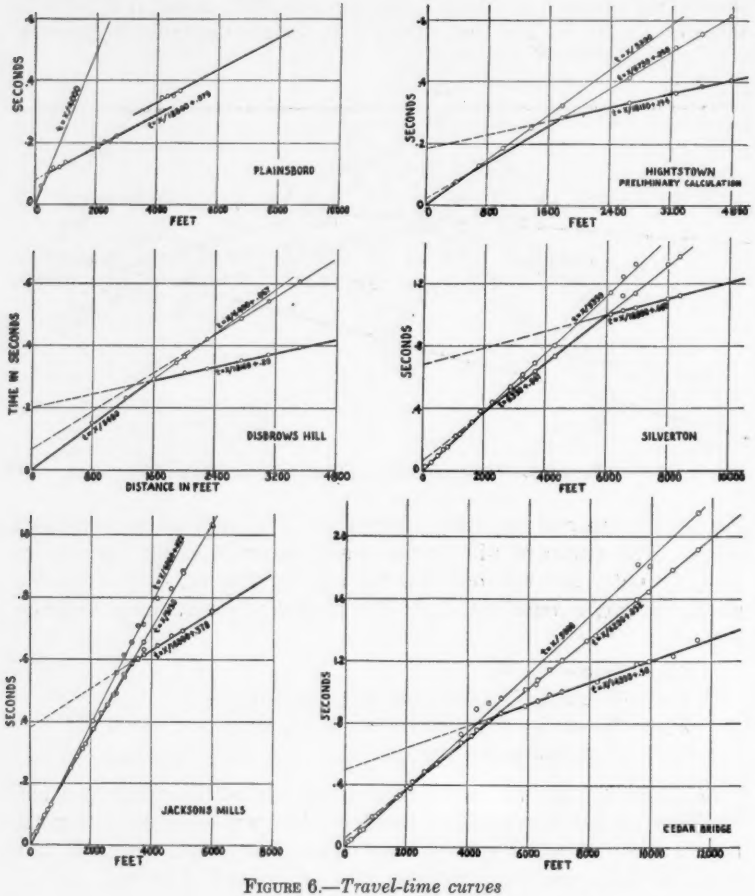

FIGURE 6.—*Travel-time curves*

TRAVEL-TIME DATA AND GEOPHYSICAL RESULTS

GENERAL STATEMENT

In this section all of the travel-time data are presented in the form of graphs in Figures 6 to 9. The equation for each straight line in these graphs was determined by least squares, and the apparent velocity so obtained is written beside the line. These data, together with the depths,

slopes, and velocities calculated from them, are summarized in Table 1.

All station maps are included in Figures 10 and 11 to show the relative positions of shot and recording points. This information gives the control on slope at stations where reversed profiles were not run. (Ewing, Crary, and Rutherford, 1937, p. 764.)

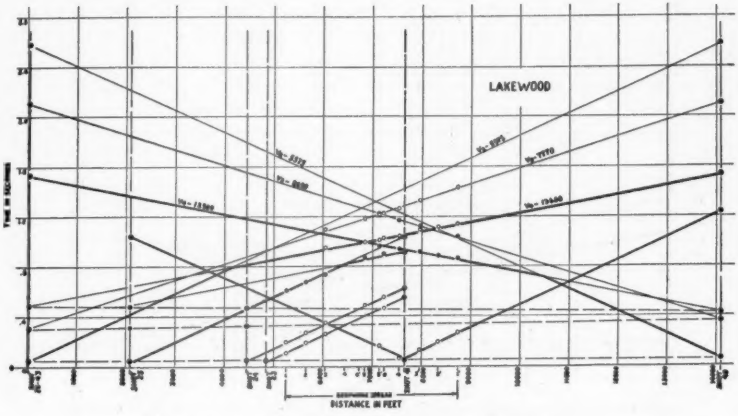

FIGURE 7.—*Travel-time curve for Lakewood*

SILVERTON

The Silverton station is at the seaward end of the section. The *M* horizon was not detected, probably because it was masked by the *V* horizon. If the *M* horizon is actually present, and if it has about the velocity and stratigraphic position observed for it at Lakewood, the actual depth to basement is probably about 170 feet greater than that given.

CEDAR BRIDGE

If the *M* horizon has also been overlooked at Cedar Bridge, the depth to basement should be increased about 120 feet above that given. Several points have been plotted on the travel-time graph which are not on any branch of the curve as it is now drawn. They are included because they were very definite arrivals on the seismogram, and because a careful search was being made for points indicating the presence of the *M* horizon. No use was made of these points in the calculations.

LAKEWOOD

On the travel-time graph for Lakewood, Figure 7, "reverse points" and "time-intercept points" are indicated by circles, to serve as an

example of the conditions which a set of overlapping profiles must satisfy in order to be self-consistent. It is seen that the V_2 lines have time-intercepts at this station, which indicate the presence of a "weathered layer." The velocity in the weathered layer was assumed to be 1600

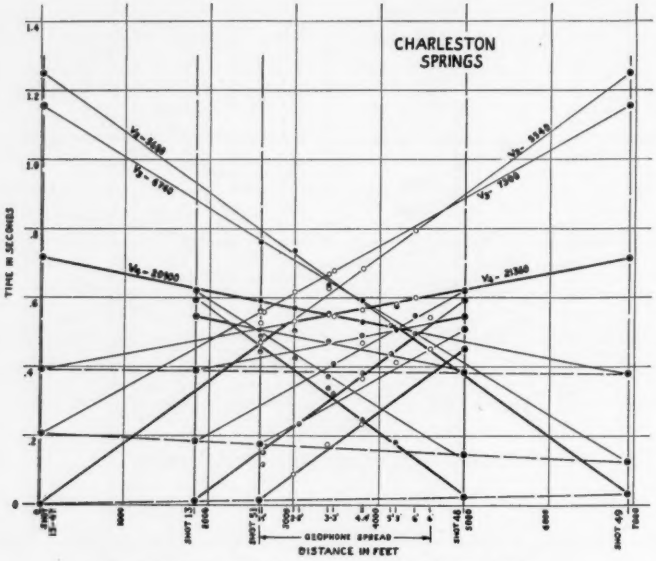

FIGURE 8.—*Travel-time curve for Charleston Springs*

feet per second, and its depth, by use of the formulas of the preceding section, was calculated to be 40 feet. This velocity and depth are consistent with local geologic conditions. The surface formation was Cohansey Sand, an unconsolidated late Tertiary sand, and the water table was deeper than the shot holes for all shots except No. 43.

The velocity 13,000 feet per second found for the basement at this station is well-established, as may be seen from the travel-time graph.

JACKSON'S MILLS

The travel-time graph at Jackson's Mills is well-determined. The *M* horizon is absent or masked. If it is only masked, the depth given for basement is about 70 feet shallow.

CHARLESTON SPRINGS

The velocity 21,060 feet per second for basement at this station is well established as shown in Figure 8 and represents a real variation in base-

ment rocks. The weathered layer present here was treated like that at Lakewood, and is again in accordance with local geology, for this profile line crosses an outlier of the Cohansey Sand.

The complexity of the travel-time graph results from the large number

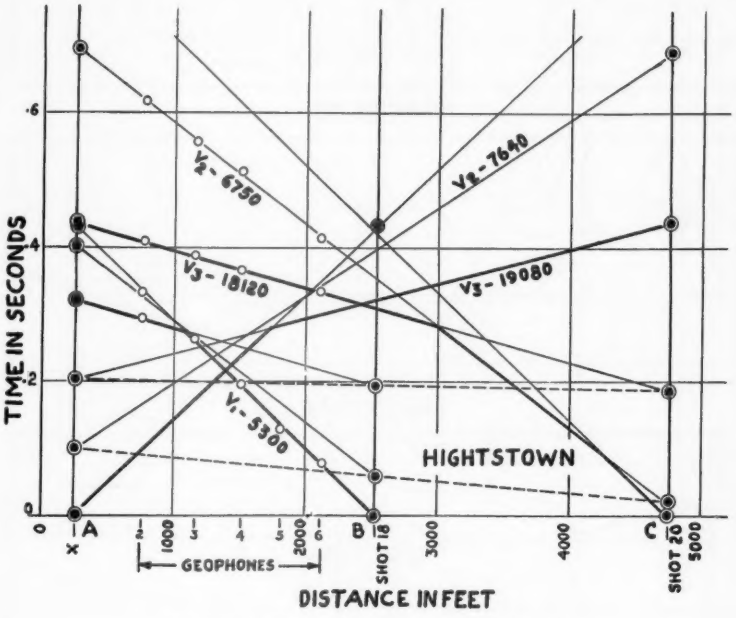

FIGURE 9.—*Travel-time curve for Hightstown*

of profiles and observed points. The use of the conditions for time-intercept points and for reverse points, which are stated in an earlier section, made it possible to have a self-consistent solution for all of the data.

DIS BROW'S HILL

The velocities observed are normal for the region, and the depths are in agreement with geologic conditions believed to exist here.

HIGHTSTOWN

The Hightstown station offers an excellent example of the advantages which may be gained by using reverse points and time-intercept points for calculations on composite profiles. The actual positions of the five geophones and of the two shot positions are shown in Figures 10 and 11.

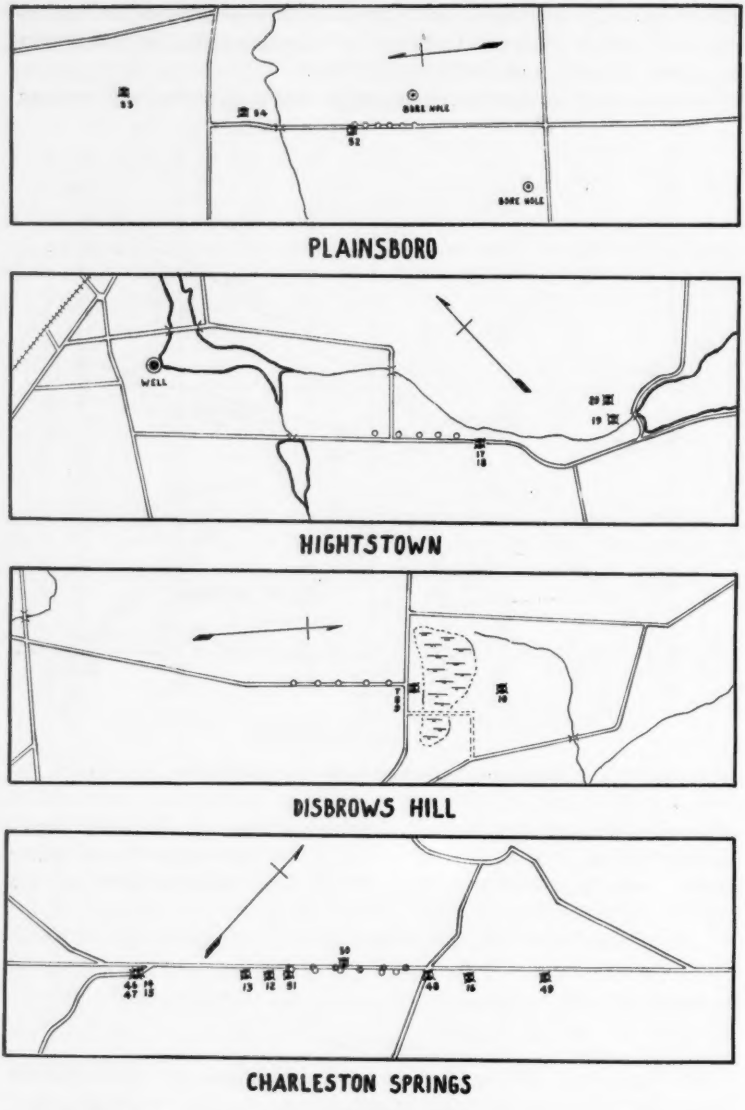

FIGURE 10.—*Seismic refraction stations*

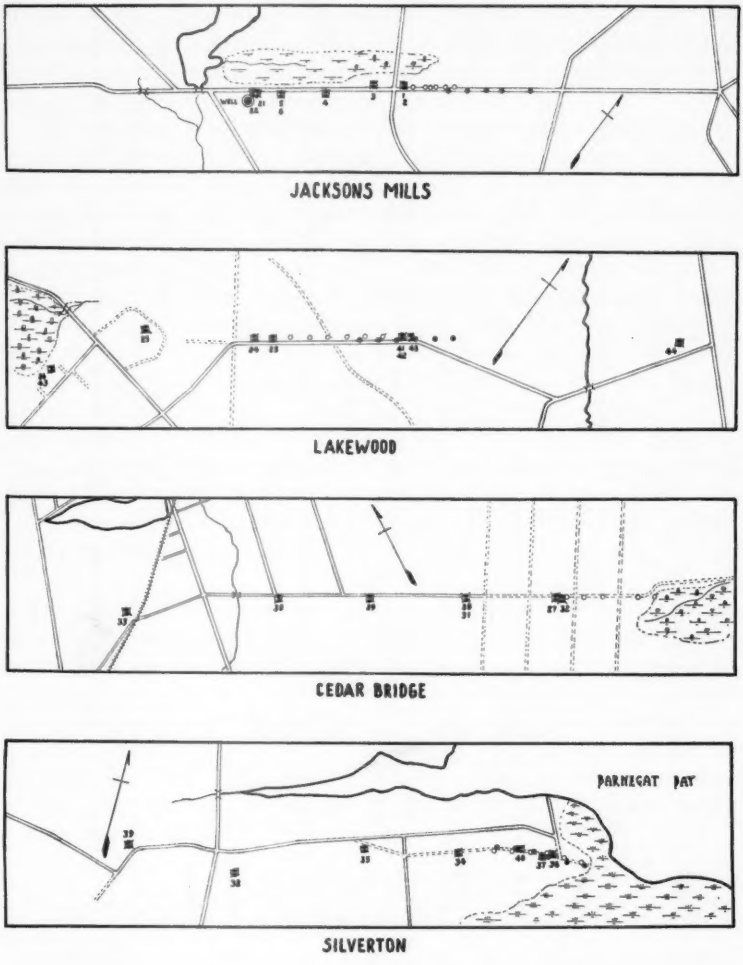

FIGURE 11.—*Seismic refraction stations*

TABLE 1.—*Summary of seismic results*

Location	Elevation ft.	V_1 ft./sec.	V_2 ft./sec.	V_3 ft./sec.	V_4 ft./sec.	T_1 sec.	T_2 sec.	T_3 sec.	H_1 ft.	H_2 ft.	H_3 ft.	H ft.
Plainsboro	100	4000	18800			.079			164			164
Hightstown	110	5300	7640+ 6750− 7140	19080+ 18120− 18500		.058	.194		+3°56′ 229	−1°0′ 430		660
Dis Brow's Hill	140	5480	6400	18100		.067	.200		360	254		614
Charleston Springs	175	1600	5540+ 5680− 5610	7300+ 6740− 6970	21360+ 20900− 21060	.010	.184	.388	−12′ 8	+4°16′ 823	−16′ 355	1190
Jackson's Mills	115	5150	6000	16000		.022	.378		110	1090		1200
Lakewood	130	1600	5575+ 5575− 5575	8050+ 7770− 7900	12500+ 13600− 13000	.050	.312	.480	0°0′ 42	+55′ 1030	−2°23′ 465	1540
Cedar Bridge	60	5400	6200	14200		.052	.500		262	1410		1670
Silverton	10	5350	6350	18800		.061	.697		308	1910		2220

(1) Depths in last column have been rounded off to nearest 10 feet.
(2) Angles indicated in columns H_1, H_2, and H_3 represent slopes in the corresponding interfaces, measured with respect to the mean surface of the ground, taken over the line of the station.

In the preliminary treatment of the data (Fig. 6), the travel-time data from both shots were combined to form a single curve. This procedure involves the assumption that slopes are absent. The resulting graph is obviously inconsistent, indicating the presence of slope.

Figure 9 shows these same data plotted as two partial profiles B and C, corresponding to the actual positions of shot and recording points. The 5300 feet per second line of profile B was drawn first, and the V_1 lines of the other two profiles were drawn using the same velocity. The 6750 feet per second line on profile C was drawn through the observed points, and the corresponding line on profile B was drawn parallel to it and just high enough to remove the conflict indicated in the preliminary graph. The position of this line is confirmed by the later phase on geophone 2 from shot 18. The 18,120 feet per second line on profile C was drawn through observed points, and the corresponding line on profile B was drawn parallel to it and through the single available observed point. The complete reverse profile A was constructed by making its time-intercept points collinear with those of B and C, and its reverse points equal to those of C. These profiles permit a self-consistent solution of the travel-time data, which incidentally is in good agreement with the geologic data from wells.

PLAINSBORO

The continuity of the 18,000 feet per second line for Shots 52 and 54 proves the continuity of the V_1V_2 interface and also the absence of slope in it. The offset in this line for Shot 53 indicates a delay, due either to low speed basement rock between shot positions 53 and 54 or to increased depth to basement at Shot 53. All seismograms from Shot 53 were radically different in character from any other records obtained on the Barnegat Bay Section, the higher frequency components of motion being absent. No abnormal surface indications were observed, which would account for the change in record character.

SUMMARY OF RESULTS

The velocities, slopes, and depths obtained at each station are summarized in Table 1.

These results are shown on the geologic section in Figure 12 and will be discussed in detail in the next section.

GEOLOGIC SIGNIFICANCE OF RESULTS

GENERAL STATEMENT

In the Introduction it was pointed out that the present seismic investigation was located on a section that would provide sufficient well data to allow a geological check of the seismic results. In order that the reader

may have a clearer conception of the problems of correlating the seismic and geologic data a résumé of the geology of the area is presented.

GEOLOGY

Coastal Plain structure.—The Coastal Plain sediments in New Jersey overlie for the most part crystalline basement rocks of pre-Cambrian age, presumably the Wissahickon Schist. However, near the western edge of the Coastal Plain these sediments overlie the edge of the Triassic Basin in certain localities. Although the location of the section line was determined primarily by the direction of regional dip and the location of wells reaching "basement," the writers expressly avoided sections known to overlie the Triassic. That they failed in this last respect was not known until after the results had been obtained for Plainsboro, the last station of the profile.

Coastal Plain stratigraphy.—The Coastal Plain sediments overlying the basement rocks along this section are of Upper Cretaceous and Tertiary age, and are composed largely of unconsolidated sands, clays and marls. The results of the present survey, however, indicate that perhaps two lithologic *breaks* are present in these sediments. In an effort to determine the geologic significance of these indicated changes in lithology, the logs of wells in the vicinity of the seismic stations were studied.

Geologic identification of sedimentary seismic discontinuities.—The Jackson's Mills well log showed rock at 103 feet against a calculated depth of 110 feet for the seismic *break*, and the Lakewood well log gave a check of within 10 feet for the *break*. This so encouraged the writers that a geologic section along the line of survey was constructed from well logs so that a correlation might be recognized at the other seismic stations if one existed.

BARNEGAT BAY GEOLOGIC SECTION

Construction of section.—Twelve well records close to the seismic line were available, and from these a geologic section was constructed. The method employed was:

(1) To plot to scale the actual reported logs at their true positions.

(2) To determine dip for the various horizons in feet per mile from these plotted logs.

(3) To construct vector diagrams plotted so that the observed dip vector occupied its true azimuth position and had a common origin with the line of true dip. The vector value for the amount of true dip is the intercept on this line made by a perpendicular to it erected from the extremity of the observed dip vector.

(4) To move the wells perpendicularly over to the section line and replot there. This was done by resolving the vector value of dip determined above into two components, one in a north-south direction and the other in an east-west direction. The shift of the well was then determined in these two directions, and by paying attention to sign, a correction was simply determined by multiplying the respective dip component values by the distance moved and taking their sum. This was done for each stratigraphic break in the geologic column where the dip was observed to vary.

(5) These corrected logs were then replotted as being the values along the section line. The stratigraphic units thus shown were drawn in and connected with the surface outcrops as determined from a geologic map which the writers had constructed for the section from various published and unpublished data.

Corrections for well logs.—The following table gives the observed and adjusted well logs that were used in constructing the geologic section. The Jackson's Mills log is incomplete inasmuch as this log is not available for publication.

Variations in dip.—It was first thought that variations in the dip of the sediments in crossing the Coastal Plain would be negligible, but that this is not the case is shown by the following table of adjusted dips for the section. A comparison of these data with the section of Figure 12 clearly shows that "structures" are present in the Coastal Plain sediments. It also shows that the seismic data give excellent agreement for the amount of dip indicated and the structure present.

GEOLOGIC SEISMIC RELATIONS IN SEDIMENTARY COLUMN

Agreement of seismic dip and geologic dip.—In Table 3 it is noted that the dips determined from the seismic logs agree very well with those determined from the well logs for the Vincentown formation (seismic *V* horizon), and also for the seismic *M* horizon, here tentatively identified as being perhaps the Raritan-Magothy contact. This latter geologic correlation cannot be definitely established since none of the well data differentiated between these two formations except at the well at Elys Corners. Here the seismic *break* is indicated a few feet below the reported Raritan-Magothy contact, and it is on these data that the present tentative correlation is based plus the general agreement in dip noted between this seismic horizon and that of the overlying sediments.

Velocity variations in geologic units.—It will be seen on consulting the summary table for velocities, Table 4, that the two seismic horizons in the

TABLE 2.—*Observed and adjusted well logs*
Barnegat Bay section

Station	Walker Gordon Plainsboro		Hightstown		Elys Corners		Jackson's Mills		Lakewood		Mantoloking		Normandie Beach	
	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.	Obs.	Adj.
Elevation	60′	60′	108′	110′	178′	170′	110′	110′	70′	50′	−8′	0	8′	0
Base of														
Pleistocene	+30	+30	+98	+100	+173	+165			+10		−12			
Cohansey														
Kirkwood									−49	−50	−242	−247	−250	−253
Shark River									−68	−70	−272	−279	−270	−273
Manasquan							+7	+7	−165	−167	−302	−306	−370	−374
Vincentown									−230	−232	−472	−480	−490	−496
Hornerstown									−248	−250			−520	−526
Red Bk. & Tinton							−222	−222	−267	−269	−692	−706	−705	−711
Navesink					+168				−321	−323	−722	−736	−740	−746
Mt. Laurel—														
Wenonah					+93	+99	−375	−375	−403	−415	−822	−835	−840	−846
Marshalltown					+63	+69			−448	−450	−852	−865	−870	−876
Englishtown					+13	+19			−536 (+)	−538 (+)	−1002	−1017	−1030	−1038
Woodbury					−32	−25	−582	−582			−1072	−1087	−1110	−1118
Merchantville			−2		−167	−160	−644	−644			−1192 (+)	−1207 (+)	−1170 (+)	−1180 (+)
Magothy					−237	−230								
Raritan			−374	−372	−286 (+)	−279 (+)	−1226	−1226						
Brunswick														
Lockatong														
Stockton	660 (+)	660 (+)												
Crystalline Surface			−374	−372			−1226	−1226						
Total Depth	660	660	−393	−391	−286	−279	−5000	−5000	−536	−538	−11792	−1207	−1170	−1180

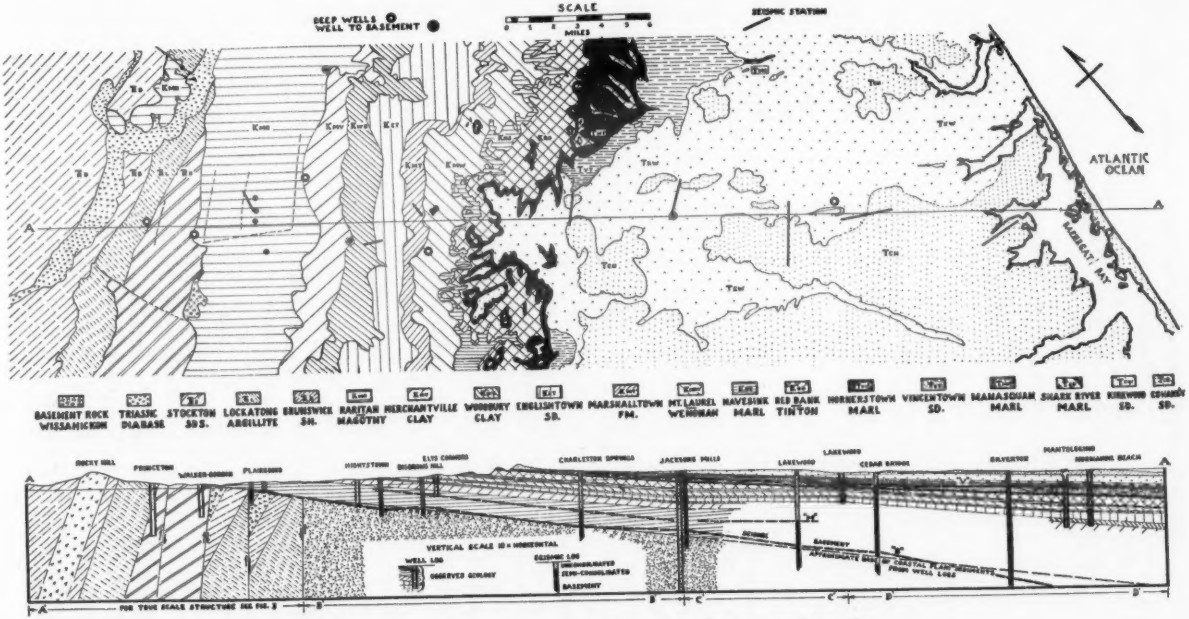

FIGURE 12.—*Barnegat Bay, New Jersey, geologic-seismic section*

TABLE 3.—*Variations of dip, Barnegat Bay section*

(Feet per mile)

Part 1. Based on well logs

Formation	Sections of Figure 12			
	A	B	C	D
Kirkwood	.....	21	21	18
Unconformity				
Shark River	.....	.....	23	24
Unconformity				
Manasquan	.....	32	25	15
Vincentown	.....	32	26	27
Hornerstown	.....	33	26	28
Unconformity				
Red Bank	.....	48	6	46
Navesink	.....	48	6	44
Mt. Laurel–Wenonah	35	46	6	44
Marshalltown	.....	46	6	44
Englishtown	38	50	6	53
Woodbury	40	50	.....	.....
Merchantville	48	50	.....	.....
Unconformity				
Magothy	No data			
Unconformity				
Raritan	65	65	66	.....
Unconformity				
Basement surface	65	65	66	.....

Part 2. Based on seismic data

V Horizon (Vincentown)	.....	32	28	28
M Horizon (Magothy ?)	.....	65	68	.....
B Horizon (Basement surface)	65	65	68	160

overlying sediments, *V* and *M*, are characterized by rather consistent velocities. This criterion, however, can not be used exclusively for identifying seismic layers as is shown by the varying values obtained for the "basement," seismic horizon *B*.

Other criteria for identification.—Other criteria used for the correlation of seismic data with the geologic are the wave characteristics as shown on the seismograms, and the calculated depths to the seismic discontinuities. This latter criterion is of value only when the general regional structure

TABLE 4.—*Seismic horizon velocities*
(Feet per second)

Station	Surface Layer	*M* Horizon	*V* Horizon	*B* Horizon
Plainsboro	4000	.....	.....	18,800
Hightstown	5300	7140	.....	18,500
Dis Brow's Hill	5480	6400	.....	18,100
Charleston Springs	5610	6970	.....	21,060
Jackson's Mills	5150	.....	6000	16,000
Lakewood	5575	7900	.....	13,000
Cedar Bridge	5400	.....	6200	14,200
Silverton	5350	.....	6350	18,800

is known from other data. In areas of as simple structure as the Coastal Plain the depth factor is very useful, but in areas of complex structure it is best to use other criteria.

SIGNIFICANCE OF BASEMENT VELOCITY VARIATIONS

General statement.—In Table 4 it is seen that the velocities recorded for the basement at the various seismic stations varied considerably, 13,000 feet per second to 21,000 feet per second. It was thought at first that perhaps small blocks of Triassic sediments might offer the explanation for these velocity variations. However, since a differential of 2000 feet per second was noted between Hightstown and Jackson's Mills, the two localities where the basement rock was reached and where the character of the rock was known from the well cuttings to be practically the same,[1] it was thought advisable to examine other data that might have a bearing upon this problem.

Virginia velocity variations.—It was found that a marked similarity existed for both the magnitude and spread of the velocities observed in New Jersey and in Virginia. Since gravity data were available for the Virginia profile that had been determined since the completion of the seismic profile there, these data were also examined.

[1] Both wells entered typical Wissahickon schist with abundant metamorphic minerals. The Hightstown group showed perhaps a higher degree of metamorphism.

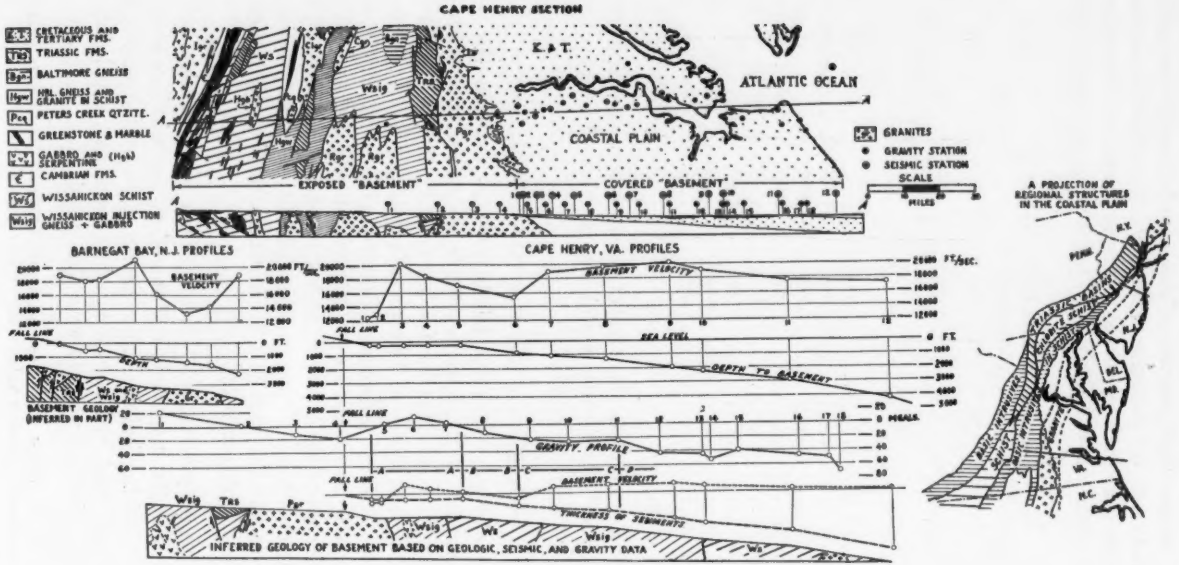

FIGURE 13.—*Basement character analysis*

Seismic-gravity correlations in Virginia.—Swick (1937, p. 333) had pointed out that although the line of gravity stations had been established along the same line as the seismic stations in Virginia there was no general agreement between the gravity anomalies and seismic depth. As such a correlation would be expected if the gravity anomalies were due primarily to the thickness of sediments underlying the stations, the indications were that other factors must be present which exerted a marked effect upon the anomalies. As any unknown factors that would have a marked effect upon the gravity might also affect the seismic velocities a detailed examination of all the Virginia data was made. Figure 13 shows comparative velocity graphs for the Barnegat Bay, New Jersey, and Cape Henry, Virginia, sections, and in addition shows the Virginia seismic depth, velocity, and gravity data plotted on comparable scales.

Indications of seismic-gravity data in Virginia and New Jersey.—There are two things that are strikingly indicated by Figure 13. First, that not only are the velocity variations in Virginia and New Jersey of about the same magnitude and spread, 13,000 feet per second to 21,000 feet per second, but the distribution is such as to give two velocity troughs of about the same lateral spread. This would indicate that possibly the area of low velocities is a regional feature in the basement which extends up the coast from Virginia into New Jersey. Second, that over that portion of the Virginia profile where the depth of sediments is constant the velocity and gravity anomaly curve parallel each other in trend; in that portion where the sediments increase and the velocity rises, the gravity curve flattens out; and finally for that portion of the profile where the velocity is practically constant the gravity curve slopes off in agreement with the increasing thickness of sediments.

The second observation appears to indicate that the gravity is subject to two forces, the thickness of low density sediments and the lateral density variations which apparently affect both the gravity and the seismic velocities alike. If these deductions are true, then an examination of the lithology of the exposed basement rocks across the Fall Line would presumably give a clue as to the nature of the disturbing factor.

CORRELATIONS OF LITHOLOGY AND GRAVITY

Piedmont area of Virginia.—The seismic line on the Cape Henry Section stops at the Fall Line, but the gravity profile was extended across into the Piedmont area so that four stations fall in this region. An examination of these data shows that a marked high of plus 31 milligals exists over the Wissahickon schist that has been altered by gabbro intrusions into an injection gneiss, and that a low of minus 10 milligals exists over the Petersburg granite, which is the basement rock outcropping at the Fall

Line from under the Coastal Plain sediments. These anomaly values are in agreement with gravity observations over similar rocks in other areas of the Piedmont and can be regarded as representative.

Coastal Plain area of Virginia.—If we interpret the gravity results observed over the twenty mile shelf in the basement out from Petersburg in the light of the above, it would appear that the basement lithology soon changes from the Petersburg granite present at the Fall Line, to a lithology similar to the Wissahickon injection gneiss. This is in agreement with the geologic data available since the Petersburg granite has been classified as of epi-Carboniferous age and intrusive into the much older schist.

Relation to seismic velocities.—The minimum seismic velocity value, observed at the same locality as the gravity minimum, appears, therefore, to be due to the granite, and the seismic velocity maximum which occurs in the same locality as the gravity peak appears to be due to the Wissahickon injection gneiss. The portion of the profile designated by B–B on Figure 13 indicates an intermediate seismic velocity after the high and decreasing gravity values with a thickening of sediments. These conditions are interpreted as representing a lithology intermediate in physical properties between the Petersburg granite and the Wissahickon injection gneiss, presumably the unaltered Wissahickon schist. In the area C–C, the flattening of the gravity curve despite the thickening of the sediments is interpreted in the light of the increase in the seismic velocities as representing a recurrence of possible Wissahickon injection gneiss. Beyond this area the gravity reflects primarily the mass of low density sediments, and the only clue as to possible basement lithology is revealed by the seismic velocities which show a decrease in value corresponding perhaps to unaltered Wissahickon schist.

Significance in New Jersey.—If the areas of low velocity in the Coastal Plain of both Virginia and New Jersey are due to the same lithology, it would appear that perhaps the belt of granites on the edge of the Coastal Plain in Virginia swing up under the Coastal Plain of New Jersey and may therefore be continuous with the Paleozoic granites of Connecticut and Rhode Island. As a possible check on this indication the granites were projected in conformity with the regional structures up the coast under the Coastal Plain as shown on Figure 13, and it was found that if they are present in New Jersey they probably pass through the area in which the low seismic velocities in the basement were recorded.[2]

[2] Since the completion of this work the writers have been notified by Meredith Johnson, New Jersey State Geologist, that two wells in southern New Jersey which reached basement in the projected area of granites actually drilled into rocks of an apparent granitic nature.

DISCUSSION OF SEISMIC-LITHOLOGIC CORRELATIONS

Velocity-density relations.—The correlation of velocity and density has been noted by other investigators, and in general plutonic rocks of high density are characterized by high velocities. Ide (1936, p. 81) gives density and elasticity values for several plutonic rocks determined by dynamic laboratory methods. Jeffreys (1929, p. 120) lists density and bulk modulus values for other plutonic rocks. Woollard (1934, p. 50) in testing the physical properties of Georgia building stones measured the elastic and density properties of various rocks and minerals. The results of these investigations indicate that in general elasticity increases with density, and this increase is greater than the increase in density. The velocity, therefore, which depends on the ratio of elasticity to density, generally increases also with the density.

These laboratory results therefore appear to confirm the evidence of the field gravity and seismic data in Virginia.

Granite-velocity correlations.—Although the present seismic velocity correlations with lithology appear to be fairly well supported by the available geologic data, the point cannot be overlooked that no previous investigators have found granite velocities as low as those here tentatively assigned to granite. Ewing and Leet (1932, p. 160) found an average velocity value of 16,530 feet per second for three New England granites, and Weatherby, Born and Harding (1934, p. 106) found a value of 17,950 feet per second for the Tishmingo granite in Oklahoma. However, it is interesting to note that the observed velocities in this latter case varied considerably with the span of the seismic profile used in making the measurements. For short spans the value dropped to 14,880 feet per second, whereas the long spans, up to 2500 feet, yielded the higher value. It was thought that perhaps the depth of penetration of the seismic waves and the variation of the water content of the rock might offer an explanation of the phenomenon. A possible sampling error might exist also, but no definite data were available that would permit an absolute check on these.

EVIDENCE FOR CORRELATING NEW JERSEY "*M*" AND VIRGINIA "SEMI-CONSOLIDATED" LAYERS

General statement.—The additional seismic data obtained from the New Jersey investigation coupled with more well log material are believed to furnish a clue as to the identity of the "semi-consolidated" seismic layer noted on the Cape Henry profile in Virginia.

As previously pointed out the *M* horizon in New Jersey occupies a stratigraphic position just below the reported Raritan-Magothy contact, and it is found from a study of recent well material that the Virginia

"semi-consolidated" horizon occupies a similar stratigraphic position. This is seen by a comparison of the seismic logs with the logs for the four deep wells in the Norfolk-Mathews Area—Mathews, Chamberlin, Ft. Monroe, and Moore's Bridge—as shown in Figure 14.

Although no published stratigraphic division of these logs is available, the writers were fortunate in obtaining the use of these data in unpublished form from the Committee for the Study of Continents of the American Geophysical Union.

The marked agreement of the seismic break with the indicated Raritan-Magothy contact at these wells suggests that the relation is a real one. The similar position to that observed for the *M* break in New Jersey further suggests that the horizon is continuous up the Coast. Lack of authentic well data between the two points, however, prevents a complete geologic check upon this possible condition, but an additional seismic profile which is contemplated across the southern portion of New Jersey should give some information on this point.

Velocity evidence.—Another check as to whether these intermediate seismic horizons in Virginia and New Jersey are the same is afforded by the seismic velocity data as shown in the following table.

New Jersey		Virginia	
Station	Velocity *M* Horizon (Ft./sec.)	Station	Velocity "Semi-consolidated" (Ft./sec.)
Hightstown	7140	Mulberry Island	6331
Dis Brow's Hill	6400	Hampton	6714
Charleston Springs	6970	Ft. Monroe	6800
Lakewood	7900	Cape Henry	7347
Average Value	7192	Sea Station No. 8	7640
		Sea Station No. 12	7435
		Average Value	7046

The marked similarity in velocities is obvious especially when contrasted with the average value for the *V* horizon in New Jersey (6150 feet per second) and the average basement velocity of about 18,000 feet per second in both Virginia and New Jersey.

Nature of M Horizon in New Jersey and Virginia.—It will be seen on consulting Table 1 that the *M* horizon was not detected throughout the New Jersey Section. The absence of this horizon at the Jackson's Mills, Cedar Bridge, and Silverton stations the writers believe is directly due to the masking effect of the earlier shallow *V* horizon arrivals on the seismograms rather than the actual physical absence of the horizon. Although no data that bear upon this point are at present available, it is hoped that it will be possible to make vertical velocity measurements

in a well casing at Normandie Beach which might throw some light upon the problem. The effect of neglecting this horizon, if it is present, upon the depth calculations has already been mentioned in an earlier section of the paper and needs no further discussion here.

The nature of the *M* horizon in Virginia, if the "semi-consolidated"

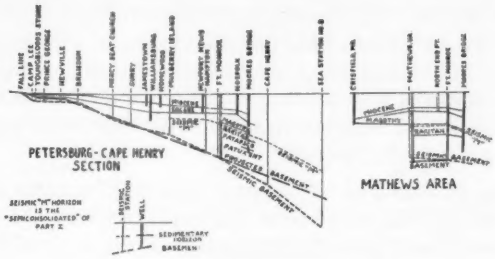

FIGURE 14.—*Virginia seismic-geologic sections*

layer there is the equivalent of the New Jersey horizon, and it appears to be on both geologic and seismic evidence, is continuous from the Mulberry Island station where it was first detected to at least Sea Station No. 12. No equivalent of the *V* horizon determined in New Jersey is indicated by the velocities all of which lie in the *M* horizon range. The wide area over which they occur further indicates that the New Jersey *M* horizon might well be continuous although it could not be seismically determined.

Cape Henry geologic-seismic profile.—Figure 14 shows a comparison of the seismic profile from Petersburg through Cape Henry with a geologic profile from Richmond to Cape Henry based upon the work of Darton (1896, p. 175). It also shows newly acquired data for the wells at the seaward end of the profile.

It is interesting that the seismically defined platform in the basement extending out from Petersburg, which is about 20 miles wide with a mean depth of about 300 feet below the surface, is duplicated by Darton from well data as extending out from Richmond about 15 miles at a depth of about 150 feet. The significance of this phenomenon, however, cannot be explained at this time as there are insufficient data.

It is also seen that not only does the "semi-consolidated" seismic layer occupy the same stratigraphic position at certain wells on the coast, but also there is a marked agreement in slope between it and the Raritan-Magothy contact both along the Cape Henry Section and also on the

short included section from the Mathews well on the north to the Cape Henry area. This structural agreement in addition to the previously mentioned correlation suggests to the writers that the two horizons correlated in Virginia and New Jersey are one and the same.

ACCURACY OF DEPTH DETERMINATIONS

General statement.—On Figure 12 it is seen that the seismic depths approximate very well the basement surface determined by a line drawn between the two elevations on the basement from the wells at Hightstown and Jackson's Mills. For individual stations the check on depth is found to be within 30 feet at Hightstown and 130 feet at Jackson's Mills. This difference at Jackson's Mills amounts to 10 percent as the well indicates basement at a depth of 1336 feet.

Significance of Jackson's Mills depth value.—The large discrepancy noted at Jackson's Mills may be the result of the neglect of the *M* horizon which was not detected here on the seismogram record, or of local irregularities in the basement surface.

In the seismic method the depth measured is an average value for the entire seismic profile rather than at a single point. As at this station the profile was a mile and a half long, and the well situated at one end of the profile, it is not surprising that the average depth determination made is not in agreement with the well if one thinks of the basement surface as an erosional one rather than a plane.

The degree of error in the depth determination that may have been introduced by the neglect of the undetected *M* horizon has already been discussed in a previous section. It was seen that even if this horizon were present there would still remain a difference of about 55 feet between the determined depth and the well depth. It is therefore essential that some idea of the amount of relief present in the basement be determined if a correct evaluation of the present work is to be had.

Basement relief.—In order to check the magnitude of the relief indicated seismically for the basement, and also to obtain some idea as to the lateral variations in relief, a copy of the detailed Basement Map made by Matthews (1932) from well data in the vicinity of Baltimore, was obtained from the Maryland Geological Survey. Sections from this map plotted on the same vertical and horizontal scale as the seismic results in New Jersey are shown in Figure 15.

It is noted first, that the relief indicated for the basement in New Jersey, about 280 feet, is practically identical with that indicated by the well data for the basement in the vicinity of Baltimore, 285 feet. Second, the Baltimore sections show that within half a mile it is quite possible to get changes in relief of 200 feet or more.

Therefore, in the light of these data the writers do not attach any great significance to the lack of check on the well at Jackson's Mills, since even if part of the discrepancy is not due to the undetected *M* horizon, known variations in relief in other areas more than cover the indicated deviations here.

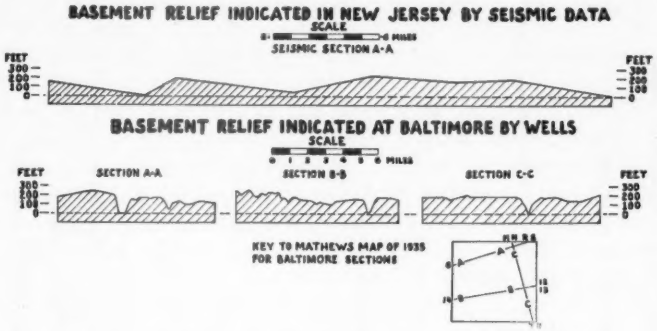

FIGURE 15.—*Basement relief in New Jersey and Maryland*

Slope conditions.—For the section from Jackson's Mills to Cedar Bridge it is seen that the seismic basement line agrees very well in general slope and position with the projected basement line based upon the two wells. Beyond this point the seismic basement is shown to dip at an increasing rate, and this is in agreement with the results noted for the outer portion of the Virginia seismic profile.

It might also be added that this marked increase in slope on the seaward end of the profile is in agreement with gravitational data not only in Virginia but at other points in the Coastal Plain where sufficient gravity data are available. It also is in agreement with the sub-surface structural study made by Thom (1937, p. 316) for the Atlantic Coastal Plain which is based upon well data.

PLAINSBORO

General statement.—This station was established to give an intermediate depth determination for the basement between that reported in the well at Hightstown and the surface outcrop at Princeton Junction. However, even before the travel-times had been measured on the records it was apparent from the record character that sub-surface conditions at the station were radically different from those at the other stations on the section.

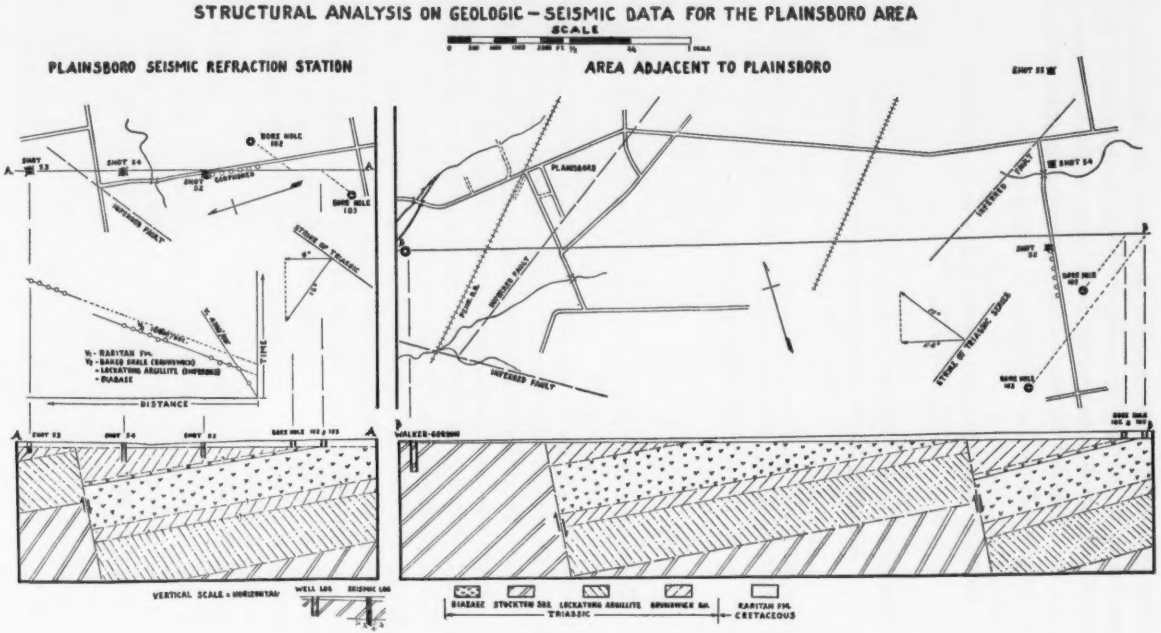

FIGURE 16.—*Geologic-seismic analysis for Plainsboro area*

Physical conditions indicated by seismic measurements.—As pointed out in an earlier section, inspection of the travel-time graph indicated a basement without slope between Shots 52 and 54. (*See* Figure 16.) Further, the depth indicated (160 feet) plots on the line drawn between the Hightstown well elevation for the basement and the outcrop, and the observed velocity (18,800 feet) is in agreement with the average value observed elsewhere for the basement. These various data suggest that the results were satisfactory. However, the additional shot, No. 53, beyond shot position 54 showed that the geological conditions were different. The record character for this shot was of low frequency in contrast to the high frequency of the other shots, and the Time-Distance graph showed a marked offset in the observed points derived from the shot.

The significance of these observations was that first there was a definite change in lithology between Shots 53 and 54, and second, that this change was of such a nature that an effective filter was formed which eliminated the high frequency wave vibrations. What this meant in terms of geology, however, was not ascertained until bore hole data for the area were found in the files of the New Jersey Geological Survey.

Local bore hole data and their significance.—It was found that the United States Engineering Corps had established a line of bore holes through this part of New Jersey and that hole No. 102 was located within a hundred yards of the end geophone and indicated baked shale at a depth of 160 feet, the depth to the seismic basement based upon Shots 52 and 54. Another bore hole, No. 103, about a quarter of a mile away from the seismic profile showed that at essentially the same depth diabase was encountered. Finally a third bore hole, No. 113, a little more than 3 miles away showed that typical basement rocks existed at —19 feet.

Although no Triassic material was known to be nearer than 5 miles, it appeared from these bore hole data that Triassic material did underlie the Plainsboro seismic station, and that in addition there was a diabase intrusion. The presence of this intrusion and its baking action upon the intruded shales apparently accounts for the observed velocity of 18,800 feet per second, since it would not be expected that normal Triassic sediments would have a velocity much higher than the Cretaceous sedimentary cover. The report of typical basement rock, here Wissahickon schist, in Bore Hole 113, apparently indicated a fault boundary for the southern edge of what appeared to be a block of Triassic material under the Coastal Plain mantle. Johnson[3] has placed this fault tentatively along the course of the Millstone River as shown on Figure 16.

[3] Meredith E. Johnson, New Jersey State Geologist. Personal communication.

This strike is normal to that generally occupied by the faults in the Triassic material, but a similar trending fault has been reported by Fanshawe (1932) in the exposed Triassic near Princeton which is shown on Figure 12.

Other well data.—The eastern boundary of the Triassic block is apparently a fault since both the well at Hightstown and that at Jamesburg to the north of Hightstown showed basement rock of Wissahickon schist. This inferred fault boundary is shown on Figure 12, but there are no data to localize its position other than that it lies somewhere between Hightstown and the Plainsboro seismic station.

On the west a deep well at the Walker Gordon Dairy has been drilled into Stockton sandstone, which is the lowest member of the Triassic series. Here it lies beneath a 30 foot cover of Cretaceous material, and at a depth of 660 feet the well was still in the Stockton. This would indicate that a fault must exist between this well and the Plainsboro seismic station, since the diabase intrusions occur almost entirely in the upper member of the Triassic series, the Brunswick shale, and the observed regional dips are always about 15 degrees west.

To the north there are no well data that will serve to localize this boundary, and it has accordingly been left blank.

Structural significance of seismic and well data.—In the light of the above bore hole and well data the time offset on the time-distance graph may well represent a fault. It is obvious from a geometrical consideration of the distances and thickness values of the sediments involved that a fault at this location would not accommodate the needed displacement to give the observed conditions at the Walker Gordon well. The writers have therefore postulated another fault which has been tentatively placed along the line of the general fault boundary between the Triassic material and the crystalline rocks near the Pennsylvania Railway, as shown on Figure 16. Other interpretations that might have been placed upon the time offset on the time-distance graph are that the offset represents either a sharp dip or ravine in the peneplaned Triassic surface that was filled with low velocity sediments. The geometric considerations based upon the well data, however, tend to eliminate these in favor of a fault at this point.

Such an interpretation would indicate that possibly the change in record character observed for Shot 53 is due to the filtering action of breccia in the fault plane.

Nature of diabase intrusion.—So far the discussion has concerned itself with the structural conditions present. Another problem con-

cerns the nature of the diabase intrusion reported in Bore Hole 103. On the assumption that the intrusion follows the regional strike of the Triassic, as do most of the diabase intrusions seen in the exposed Triassic areas, it is seen that the baked shale of Bore Hole 102 lies practically at the contact of the intrusion. These data therefore yield no information as to the probable thickness of the intrusion. However, a clue is offered by the seismic data. The basement surface indicated by the data from Shots 52 and 54 is horizontal and since the Triassic material dips at an angle of 15 degrees it appears that this surface is not a stratigraphic one, but rather a truncated one, presumably of the baked shale which is present at the end geophone. If this is true, then as shown in Part A of Figure 16 the thickness of baked shale present is about 500 feet and this would indicate the presence of an intrusion of at least the size of the Rocky Hill intrusion seen in the exposed Triassic near Princeton which is 1200 feet thick.

It is quite possible that this intrusion beneath the Coastal Plain is an offset section of the Rocky Hill intrusion, just as the Rocky Hill sheet is an offset of the Lambertville sheet separated by the fault that passes through Hopewell.

Since the fault placed near the Walker Gordon Dairy lies along the same line with the general fault boundary between the Triassic Basin area and the basement rocks, it is regarded as being the main fault upon which most of the indicated displacement has taken place; the fault at the seismic station is regarded as a secondary feature of much less displacement. There is no geologic or seismic evidence that will permit an exact evaluation of the throw on this fault, and it was made just sufficient to satisfy the requirements of the seismic data (material of a lower velocity should be present at the Triassic surface between Stations 53 and 54 and thus provide the observed delay in travel-time). The change in record character here is attributed to possible filtering by breccia in the fault plane along which a displacement of about 1500 feet is indicated.[4]

CONCLUSIONS

In summarizing the results of this investigation the writers wish to stress one point in particular; that the seismic results were calculated without the benefit of any of the detailed geologic data later used for correlation. These data, all from unpublished well records, were not consulted until after the seismic results had been submitted to the New

[4] Since the completion of this work, the New Jersey State Geologist has brought to the attention of the writers, a well record which reports diabase in the intermediate area between the two faults at a depth of 235 feet where the present structural interpretation places it at 250 feet. This would indicate that the interpretation presented is essentially correct.

Jersey State Department of Geology to see if any correlation existed between the seismic and geologic horizons.

In carrying out this work the standard seismic refraction technique was used in the field, and in interpreting the records, first and second wave arrivals were used so as to permit the maximum amount of data available to be utilized. Although this technique requires a close study of wave characteristics to avoid confusion of the various later arrivals, the results indicate that few stray arrivals were thus introduced, and in no case was there any confusion in the time-distance curves.

At those stations where reverse profiles were established the new method of time-distance curve analysis introduced permitted more accurate and consistent results to be obtained than would otherwise have been possible with the same amount of data.

New formulas for computing the depths of any number of seismic layers were introduced since the existing mathematical treatment did not permit a solution for accurate depth determinations for the conditions at the Charleston Springs and Lakewood stations.

The geologic indications of the investigation were numerous and are expressed in the following summary.

(1) The basement rocks dip seaward at an approximate rate of 65 feet per mile to within a few miles of the coast where the dip increases.

(2) A dip of about twice this magnitude is indicated to the south for the basement by the reserve profiles run at Charleston Springs and Lakewood stations.

(3) Seismic velocity variations observed in the basement rock are, when considered in the light of gravitational data, due to changes in lithology apparently ranging from granite to schist much altered by basic intrusions.

(4) The lithologic variations in the basement under the Coastal Plain sediments are apparently regional features extending along the coast from Virginia through New Jersey.

(5) The order of relief indicated by the seismic data for the basement is about 280 feet, and is the same as that shown by detailed studies made from well logs for the basement in the area adjacent to Baltimore, Maryland.

(6) The probable error on depth calculations for the seismic horizons when correlated with their geologic equivalents is less than ten percent.

(7) Lithologic horizons in the overlying Raritan-Magothy and Vincentown formations can be traced with a marked degree of accuracy by the seismic method thus showing structural conditions in the overlying sediment.

(8) There is evidence that the *M* seismic horizon observed in New Jersey and the "semiconsolidated" seismic horizon observed in Virginia are the same geologic horizon.

(9) An apparent fault-bounded block of Triassic sediments extends out into an area hitherto regarded as being underlain entirely by basement rocks of presumably pre-Cambrian age.

(10) A fault of marked displacement is present in the covered Triassic material near Plainsboro.

(11) Another fault of somewhat less displacement is present in the covered Triassic material at the Plainsboro seismic station.

(12) A section of the diabase sheet seen near Lambertville and exposed by faulting at Princeton is believed to be brought up by the faults of Items 10 and 11 so as to lie at the peneplaned Triassic surface beneath the Cretaceous cover at the Plainsboro seismic station.

(13) Changes in lithology are shown by velocity variations.

(14) Structural changes and slope conditions are recognizable from the composite time-distance graphs, but a higher degree of accuracy is possible with the alternate method of analysis presented, especially when using reverse profile data.

(15) A combination of geophysical and geologic data permits geologic interpretations to be made frequently in cases where a solution would not be possible using either group of data alone.

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MARINE PLEISTOCENE OF THE GULF COASTAL PLAIN: ALABAMA, MISSISSIPPI, AND LOUISIANA

BY HORACE G. RICHARDS

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ABSTRACT

Marine Pleistocene deposits have been traced along the Coastal Plain of the Gulf of Mexico from western Florida to Texas. The fauna is essentially similar to that inhabiting the Gulf of Mexico today. Marine fossils are found up to a few feet above sea level in western Florida and Alabama. However, in the vicinity of the Mississippi Delta the Pleistocene deposits have apparently been considerably tilted, probably because of the weight of the sediments brought down the Mississippi River. Marine Pleistocene fossils are found throughout this section to a depth of at least 2400 feet from the surface in the delta south of New Orleans. The depression caused by the Mississippi River is apparently limited in extent, and marine fossils are again encountered above sea level in the Pleistocene deposits near Lake Charles, Louisiana. It is suggested that at least some of the marine deposits of this region may be correlated with the Pamlico terrace of the Atlantic Coastal Plain and consequently date from the last major interglacial stage. It is further suggested that these same marine deposits can be correlated with the Beaumont formation of Texas.

INTRODUCTION

ATLANTIC AND GULF COASTAL TERRACES

In a previous paper the writer (Richards, 1936) discussed the marine Pleistocene of the Atlantic Coastal Plain from New Jersey to Florida. Fossils were found only in the lowest terrace deposit—the Pamlico terrace and formation—with shore line at an elevation of 25 feet. Stratigraphic

and paleontologic evidence was presented to show that these deposits date from the last major interglacial stage. The terrace aspect is much less distinct north of Maryland; it was, however, suggested that the Cape May formation of New Jersey could be correlated with the Pamlico (MacClintock and Richards, 1936).

Field work along the east coast of Florida also showed that marine Pleistocene fossils were restricted to the 25-foot terrace deposit. This deposit included the Anastasia formation, the Miami oölite, and the Key Largo limestone, all of which were thought to be contemporaneous. The Fort Thompson formation may be of the same age, or parts of it may be younger (Richards, 1938a).

According to Cooke (1931) the 25-foot shore line occurs on both coasts of Florida. Leverett (1931), however, believes that there has been tilting; he recognizes the lowest terrace (Pensacola) as occurring at an elevation of 40 feet on the east coast of Florida and 25 feet on the west coast. Cooke believes that Leverett has overlooked the 25-foot shore line on the east coast and has correlated the next to the lowest terrace (Talbot) of the east coast with the lowest (Pamlico) of the west coast, thereby giving the impression of tilting. No direct paleontological evidence was found bearing on this subject. However, it may be noted that marine fossils do occur along the east coast of Florida to slightly higher elevation (25 feet) than along the west coast (10 feet). If tilting did occur because of the weight of the sediments brought down by the Mississippi River, it might explain the scarcity of fossils between the Suwannee River and Pensacola. Further data on this tilting must await the completion of more topographic maps in Florida. The following correlation of the Pleistocene of Florida was suggested (Richards, 1938a, p. 1286):

TABLE 1.—*Correlation of Florida Pleistocene*

	New Jersey to Georgia	Northern Florida	Southern Florida	Keys	Everglades	Florida and Gulf Coast
POST WISCONSIN		Melbourne bone beds			FORT THOMPSON	
WISCONSIN	EROSION	EROSION	EROSION	EROSION		EROSION
SANGAMON	PAMLICO	ANASTASIA	MIAMI OOLITE = Palm Beach l. s. = Key West oolite = Lostmans River l.s.	KEY LARGO LIMESTONE		PENSACOLA TERRACE
			Fossils from well at Delray—118 ft.			
	TALBOT		UNFOSSILIFEROUS PLEISTOCENE			Higher elevations of PENSACOLA TERRACE of Eastern Florida

Early Pleistocene or Late Pliocene

Fossils from well of Kissimmee.
Fossiliferous deposits on St. John River near Sanford.

The fauna indicated water at least as warm as that of the present; at one locality (a well at Delray) a slightly higher temperature was suggested. For this reason as well as for stratigraphic reasons, it was suggested that the lowest terrace of Florida could be correlated with the Pamlico and that it dated from the last major interglacial stage.

SCOPE AND PURPOSE OF PRESENT WORK

During the progress of the field work on the Pleistocene of the Atlantic Coastal Plain, it became desirable to attempt a correlation of these deposits with those of the Coastal Plain of the Gulf of Mexico. Therefore in the winters of 1935, 1936, and 1938 the field work was extended along the coasts of Alabama, Mississippi, Louisiana, and Texas. In the present report an attempt is made to trace the marine Pleistocene from western Florida to the Sabine River, which is the Louisiana-Texas line. The report on the Texas work will be published at a later date.

Little attempt has been made to subdivide the Pleistocene. Much of this would be based upon the recognition of shore lines, terraces, and other physiographic features. Since considerable physiographic field work is now under way on the Gulf Coastal Plain, it is thought that any attempt to correlate the fossils with physiographic features would be premature. Therefore in most cases only general correlations are suggested. The faunas of the various localities are listed and discussed in the hope that this information will be of use to future workers on the correlation of the Pleistocene of the Gulf Coastal Plain.

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The United States Engineer Office of the War Department made possible a preliminary reconnaissance trip in March 1935 to numerous excavations and fossil localities along the Intra Coastal Canal from Florida to Texas.

During the summer of 1936 a small grant was received from the Carnegie Institution of Washington for a study of the fresh-water Pleistocene mollusks from the southern and southeastern States. Thus work was carried on in September 1936, and fossils were collected from Georgia, Mississippi, Louisiana, and Arkansas (Richards, 1938b). On this trip the writer was accompanied by Professor Edgar T. Wherry, of the University of Pennsylvania and Allen L. Midyette, Jr., of Swan Quarter, North Carolina. Mr. Midyette has also kindly prepared the locality map (Plate 3).

Dr. W. Armstrong Price, Consulting Geologist of Corpus Christi, Texas,

spent a few days with the writer in southwestern Louisiana in March 1938, prior to more extensive field work in Texas.

The Geological surveys of Alabama, Mississippi, and Louisiana fully cooperated by placing at the writer's disposal both information and actual fossil material. Special thanks are due Dr. H. V. Howe and Mr. C. K. Moresi of the Department of Conservation of Louisiana, who made possible certain of the field work in that State. The writer is also indebted to Dr. Howe for courtesies extended while studying fossil material at Louisiana State University, Baton Rouge, Louisiana.

Professor G. D. Harris of the Paleontological Research Institute at Ithaca, New York, allowed the writer to spend several days examining material from the Gulf Coast, most of which had been collected by Professor Harris when he was State Geologist of Louisiana.

Additional fossil material has been examined in the collections of the United States Geological Survey and the United States National Museum in Washington, D. C., the Academy of Natural Sciences of Philadelphia, the University of Alabama, Louisiana State University and the private collection of Mr. Warren B. Reed of New Orleans, Louisiana.

The various oil companies of the Gulf Coastal Plain have cooperated by placing at the writer's disposal considerable information about localities and by giving permission to study fossils in their possession. Particular thanks must be given to Mr. S. O. Burford, of the Humble Oil and Refining Company of Lake Charles, Louisiana, who spent several days with the writer in the field in southwestern Louisiana.

PREVIOUS WORK

Probably the first important writer on the Pleistocene geology of the Gulf Coastal Plain was Hilgard (1869; 1871) who described the Port Hudson formation from the land adjacent to the Mississippi River with Port Hudson, Louisiana, as the type locality. Smith, Johnson, and Langdon (1894, p. 28-51) extended Hilgard's observations as far east as Alabama. Along the Gulf Coast east of the Mississippi River, the Port Hudson was thought to pass into a brackish phase known as the Pontchartrain clays and a marine sandy phase known as the Biloxi formation. Along the coast of Mobile Bay, they recognized associated beds containing oysters and other forms now living in the open Gulf. This phase they called the Mobile or Mon Louis Island terrace; it apparently merges into a strictly fluviatile phase known as the River Terrace or Second Bottom. This correlation is shown in Table 2.

The recognized three major factors that contribute to build up the Gulf Front of Alabama: (1) the waves of the ocean, (2) the Mississippi River, and (3) the rivers entering Mobile Bay. Since these factors,

TABLE 2.—*Correlation of Gulf Coast Pleistocene*
(After Smith, Johnson, and Langdon)

	Mississippi River	Estuarine phase	Marine phase	Mobile Bay	Alabama rivers
RECENT	PORT HUDSON	PONTCHARTRAIN CLAYS	BILOXI		1st Bottom
Pleistocene				Mon Louis or Mobile Terrace	2nd Bottom

especially the Mississippi River, are still at work in the determination of the relative position of sea and land, they realized that it was impossible to draw sharp lines between the Pleistocene and Recent in the case of the Port Hudson and Biloxi formations.

They observed two river terraces higher than the Second Bottoms; however, no fossils are reported from them except some diatoms from the vicinity of Montgomery, Alabama (Smith, Johnson, and Langdon, 1894, p. 63).

Harris (1904, p. 21-22) prefers to regard the terms Port Hudson, Biloxi, and Pontchartrain as phases of deposition rather than as stratigraphic units. He says that the various stages are repeated in southern Louisiana. He points out that material similar to the Port Hudson and Biloxi has been formed throughout Quaternary time down to the present. He moreover realizes that this material was brought to its present place by the Mississippi River and other smaller streams emptying into the Gulf of Mexico, and that there has been a consequent sinking of the land with a possible uplift in nearby regions.

Harris (1904, p. 26-27) mentions marine shells occurring down to—2100 feet in a well at Napoleonville, Louisiana, and to depths not quite so great elsewhere. Later (Harris, 1910, p. 170-173), he listed the mollusks obtained from wells drilled in Terrebonne Parish, Louisiana, and recorded Pleistocene species as deep as—2470 feet. Maury (1920; 1922) has made a study of the mollusks obtained by Harris as well as of other Gulf Coast material.

Matson (1916, p. 189) described the St. Elmo, Port Hickey, Hammond, and Pensacola terraces from the Gulf Coastal Plain but gave no elevations. The lowest terrace—the Pensacola—was regarded as a continuation of the Pensacola terrace in Florida.

Lowe (1925) summarized the Pleistocene of Mississippi and correlated it with that of Louisiana.

Leverett (1931, p. 26-27) believes that the Pensacola terrace decreases in elevation westward along the Gulf. He found an old shore line re-

ferable to the Pensacola at Tampa, Florida, 33 feet above sea level; he has followed this westward and found it at an elevation of 25 feet at Pensacola, Florida, and at 13 feet at Mandeville, Louisiana, on the shores of Lake Pontchartrain. He thinks that this tilting is due to the weight of the sediments brought down by the Mississippi River. This tilting has been questioned by Cooke (1931, p. 512).

Howe (1933; 1936) has recently called attention to the great amount of sinking in the region of the Mississippi Delta which he thinks has amounted to about 30,000 feet since the beginning of the Tertiary. He regards this sinking as due to the weight of the sediments brought down by the Mississippi River and thus speaks of the Gulf Coast as an active geosyncline (Howe, 1936, p. 82).

Very strong evidence of the sinking of the Mississippi Delta is given by Russell in his physiographic study of the region. For example, the former town of Balize near the mouth of the river has sunk at least 4 feet since the time of its abandonment about 50 years ago (Russell, 1936, p. 34-35, 199). Further evidence of submergence is based on the depths to which Indian shell mounds have sunk (Russell, 1936, p. 167-169).

The most recent study on the Pleistocene of the Gulf Coastal Plain east of the Mississippi River is that of Fisk. He believes that the Port Hickey is the youngest terrace and that "Matson's lower terraces if distinct must be local 'cut' terraces rather than alluvial ones" (Fisk, 1938b, p. 12). He dates the Port Hickey from the Peorian. His proposed correlation is shown in Table 3.

The geology of southwestern Louisiana has been discussed in a series of reports issued by the Louisiana Geological Survey: Iberia Parish

TABLE 3.—*Correlation of Gulf Coast terraces*
(After Fisk)

Western Florida Parishes, Louisiana (Fisk, 1938)	Western Gulf Coast (Doering, 1935)	Eastern Gulf Coast (Matson, 1916)	Central Louisiana (Fisk, 1938)	Southwest Louisiana (Barton, 1937)
Recent	Recent	Recent	Recent	Recent
Port Hickey Terrace	Beaumont	Pensacola Hammond Port Hickey	Prairie	Beaumont
Second Terrace	Lissie	St. Elmo ?	Montgomery	Oakdale
Higher Terraces	Willis	Cirtonelle	Bentley	Lissie
			Williana	Willis and others

(Howe and Moresi, 1931); Lafayette and St. Martin parishes (Howe and Moresi, 1933); Cameron and Vermillion parishes (Howe, Russell, and McGuirt, 1935). In these reports is recognized a series of wide seaward-sloping surfaces or terraces which are regarded as Pleistocene delta remnants.

In the marshes of southwestern Louisiana, particularly in Cameron and Vermillion parishes, a number of long narrow shell ridges rise slightly above the surrounding marshes. These ridges support a luxuriant vegetation in which large evergreen oaks form a striking feature; hence these ridges are known as cheniers from the French chêne, meaning oak. Russell and Howe (1935) have discussed the physiographic history of these cheniers which they believe were formed as beach ridges during post-Pleistocene time when the mouth of the Mississippi River was farther west. Harris collected numerous mollusks from these ridges, particularly Grand Chenier (Pl. 2, fig. 1), and these were studied by Maury (1920; 1922). More recently Hadley (Howe, Russell, and McGuirt, 1935, p. 14) has listed some shells from the cheniers in Cameron and Vermillion parishes.

Hayes and Kennedy (1903) extended the Pleistocene Beaumont formation of coastal Texas into southwestern Louisiana. Fossils were reported in the vicinity of Lake Charles, Louisiana (Howe, 1933, p. 653).

Deussen (1924, p. 111) and Doering (1935, p. 656-657) have also shown that the Beaumont extends into southwestern Louisiana and that it may be correlated with the Port Hudson formation of eastern Louisiana.

Barton (1930a; 1930b; 1937) has recognized the deltaic character of the Beaumont in southeastern Texas and southwestern Louisiana and has used the term Beaumont Deltaic Plain instead of Beaumont terrace.

DESCRIPTION OF FOSSIL LOCALITIES

ALABAMA

BALDWIN COUNTY: Matson (1916, p. 177) recorded the log of a well at Fort Morgan (1).[1] The fossils from the upper part of the well were identified by W. H. Dall who said that "the material above 1290 feet is nearly all Quaternary; that below may possibly be Pliocene". Twenty-one species were listed from the Pleistocene section.

Through the interest of the Danciger Oil Company and the Humble Oil and Refining Company, material from two additional wells at Fort Morgan (2) has been turned over to the writer for study. The top of the Miocene is thought to occur at about a depth of 1500 feet[2]. Thirty-seven species were recorded from the Pleistocene of the two wells (surface to 800 feet). Since there is no sharp line between the Pleistocene and Pliocene in the region, some of the deeper fossils may be Pliocene; however, no distinctive Pliocene species were present above 800 feet. Since the two

[1] Numbers in parentheses are locality numbers and refer to map (Pl. 3) and table of fauna.

[2] Data from Humble Oil and Refining Company.

wells are very close together, the faunas are listed jointly in the formal list at the end of the paper.

The variation between the thickness of the Pleistocene of these two wells and of the previous one (1) is difficult to understand. Probably the lower part of the supposed Pleistocene of the original well was actually Pliocene. The considerable depth in all three wells at which Pleistocene fossils occur may indicate a local sinking of the land.

MOBILE COUNTY: Smith, Johnson, and Langdon (1894, p. 47) record the following section at Mon Louis Island, on the west bank of Mobile Bay about 16 miles south of Mobile (3).

	Feet	Inches
1. Light-red, yellow, and gray mottled argillaceous sand, the clay increasing toward the bottom where signs of lamination appear	8	
2. Laminated slate, blue, fine-grained, sandy clay; pyritous and showing efflorescence of ferrous sulphate, but containing no trace of organic remains	6	
3. Highly ferruginous sandstone filled with shell casts: *Ostrea virginica, Arca transversa, Pecten* sp., *Mytilus hamatus, Cardium magnum* [=*robustum*], *Natica duplicata*		2
4. Greenish-gray mud, the same dredged out of the channel of Mobile Bay, filled with shells, mainly *Ostrea virginica and Mytilus hamatus*	3	

The locality was visited by the present writer in March 1935. The fossiliferous sandstone was found up to 3 feet above high-tide line. Below the sandstone the clay was *Ostrea* and *Mytilus* was noted. In some places both the sandstone and oyster layers dip beneath the beach. In all, eight species were found indicating shallow coastal waters of about the same temperature and salinity as the Gulf of Mexico. (*See* Plate 1, figure 1.)

MISSISSIPPI

HARRISON COUNTY: Shells have been reported from various wells in the vicinity of Biloxi (4), the type locality of the formation of that name (Smith, Johnson, and Langdon, 1894, p. 34).

Pleistocene fossils were found between the depths of 30 and 50 feet in a well at De Buys Station (5) (near Edgewater Park) and between 30 and 64 feet at Long Beach (6). (U. S. Geological Survey.)

HANCOCK COUNTY: Similar fossils have been found between 70 and 95 feet at Waveland (7). (U. S. Geological Survey.)

LOUISIANA

Before entering into a discussion of the Pleistocene fossil localities of Louisiana, it will be well to note that the entire coastal portion of the State is studded with salt domes, which have in some cases risen as much as 20,000 feet, bringing the normally deeply buried salt nearer the surface and in some cases (The Five Islands) actually above the surface of the surrounding land. These salt domes are one of the chief sources of the petroleum of southern Louisiana. As a result of this unequal elevation of the domes, it is often very difficult to correlate the subsurface formations. A formation that is deeply buried at one place may be very near the surface in a salt dome. This factor, of course, greatly complicates the study of the stratigraphy of the region.

ST. TAMMANY PARISH: Fragments of shells, probably Pleistocene, were found at shallow depths (to about 300 feet) at Holdworth Well No. 1 of the Danciger Oil Company near Slidell, Louisiana (8).

Numerous shells were collected from shallow excavations and fills near the old

FIGURE 1. PLEISTOCENE FOSSILIFEROUS SANDSTONE
Mon Louis Island, Alabama

FIGURE 2. FRESH-WATER PLEISTOCENE LOCALITY
Little Bayou Sara, Louisiana

PLEISTOCENE FOSSIL LOCALITIES IN ALABAMA AND LOUISIANA

FIGURE 1. SHELL RIDGE, GRAND CHENIER

FIGURE 2. CANAL FROM WHICH SHELLS WERE DREDGED
Near Cameron Meadows

POST-PLEISTOCENE MOLLUSK LOCALITIES IN LOUISIANA

bridge over Lake Pontchartrain (9). Since the land appears to be sinking relatively rapidly in this region, it is most probable that the shells are Recent.

ST. BERNARD PARISH: Pleistocene fossil shells were obtained between the depths of 100 and 307 feet from a well at Turkey Bayou (10) on Isle au Pitre, approximately opposite Bay St. Louis, Mississippi. (U. S. Geological Survey.)

Hilgard (1878) obtained shells from the Lake Borgne borings, made between the Mississippi River and Lake Borgne for a proposed outlet for flood waters (11). These shells were listed by Maury (1920; 1922).

PLAQUEMINES PARISH: Pleistocene coral blown from Garden Island Dome at the mouth of the Mississippi River (12) was reported by Wells (1933, p. 32). The fossils were said to have been blown from depths between 680 and 1275 feet. A warmer part of the Pleistocene may possibly be indicated because these species do not occur in the northern part of the Gulf of Mexico today. Mollusks were also reported from the 'blowout', but no collection is available for study.

Ten species of mollusks were identified from a depth of 740 feet from a well in lower Plaquemines Parish near the Mississippi River (13) (U. S. G. S. Station 9275).

ORLEANS PARISH: Several collections of shells have been obtained from wells in New Orleans:

(14) New Orleans Pumping Station No. 7, (Maury, 1920; 1922).

(15) Gymnasium Well, New Orleans, depth 1200 feet (Harris, 1910; Maury, 1920; 1922).

(16) 3 miles southwest Grunewald Hotel (U. S. G. S. Station 6325). Depth 830 feet.

(17) 500 feet from Leontine Street and Mississippi River (U. S. G. S. Station 7949).

(18) Gas well on Seegar Place, 7 miles east of New Orleans. (U. S. G. S. Station 9277). Depth 200 feet.

(19) Same well, depth 300 feet (U. S. G. S. Station 9278).[3]

JEFFERSON PARISH: Six species of mollusks were obtained by Warren B. Reed of New Orleans at a depth of 680 feet from the Hero Well, opposite New Orleans (20).

EAST BATON ROUGE PARISH: Harris (1904, p. 27) records *Rangia* at a depth of 400 feet at the Istrouma Hotel, Baton Rouge (21).

A water well at Louisiana State University Dairy Barns, Baton Rouge, yielded the following mixture of brackish-and fresh-water species at a depth of 256 feet (22):

Vivipara subpurpurea (Say) (Fresh-water)
Pleurocera acutum Rafinesque (Fresh-water)
Rangia cuneata Gray (Brackish-water)
Rangia sp. (Brackish-water)

The well is probably on a salt dome.

WEST FELICIANA PARISH: (23) At the Frank Percy Place in Sec. 90, T. 1 S, R. 4W, fossiliferous exposures can be seen in the bluff along Little Bayou Sara (Pl. 1, fig. 2). The fossils occur in a silty sand which is overlain by a loess-like material. The locality was visited with Professor H. V. Howe, of Louisiana State University, in March 1935, and many fossils were collected. A full report on the mollusks has already been published (Richards, 1938b p. 27-46) in which 13 fresh-water species and 7 land species were identified, practically all of which are known to be living in the vicinity today. The two exceptions (*Ferrissia parallela* Haldeman and *Pisidium variable* Prime) are northern species not reported as far south as Louisiana.

The fossil plants of the locality have been studied by Brown (1938, p. 59-96) who also finds a distinct northern element in the flora. From a consideration of these

[3] Hilgard (1870) recorded shells from the 630-foot artesian well at New Orleans of 1856; however, these were not available for re-study and are consequently omitted from the table.

facts Fiske (1938b) and Brown (1938) date the deposit from the Peorian interglacial stage.

Similar fresh-water mollusks are known from Bayou Manchac, Ascension Parish, Louisiana, Pinckneyville, Wilkinson County, Mississippi, and elsewhere in the region. The fauna is similar to that recorded from Little Bayou Sara, and in general a slightly cooler climate is suggested. The writer (Richards, 1938b) has recently discussed fresh-water Pleistocene of Louisiana and Mississippi.

Terrebonne Parish: Harris (1910, p. 164-173) recorded Pleistocene fossils from the three wells listed below, and the fossils were studied by Maury (1920, 1922):

(24) Knapp Well No. 1, SE part of T. 20 S, R. 19 E, on Lake Tambour, at head of Oyster Bayou. Pleistocene fossils 0-2741 feet.

(25) Knapp Well No. 2, Sec. 22, T. 19 S, R. 12 E; left bank of Alligator Bayou about three-quarters of a mile from its mouth at Alligator Point; 14 miles southeast of Belle Isle. Pleistocene fossils 1000-1920 feet.

(26) Knapp Well No. 3, Sec. 15, T. 19 S, R. 12 E; left bank mouth of Blue Hammock Bayou. Pleistocene fossils 0-1839 feet. These three wells are along the shore of Four League Bay.

According to Harris (1910, p. 170):

> "It is certainly interesting to note, in studying the shells from the Gymnasium well at New Orleans from a depth of only 1200 feet, that they comprise more new species, or species not known to be living in the Gulf waters, than are obtained in the much deeper wells in Terrebonne Parish."

The greater thickness of the Pleistocene in Terrebonne Parish may be due to the greater weight of the sediments in the Lower Delta region than in the vicinity of New Orleans. At any rate it is probable that the Knapp wells are not located on prominent uplifts.

The collection of Mr. Warren B. Reed contains shells from Avoca Well No. 1, south of Morgan City (27). The top of the Miocene is reported at 2200 feet; the shells above that horizon are undifferentiated Pliocene and Pleistocene.

Assumption Parish: Harris (1904, p. 26-27) records marine Pleistocene fossils at the depth of 2100 feet from a well at Napoleonville (28). He, however, does not list the species.

Iberia Parish: Howe and Moresi (1931, p. 99), quoting Hilgard, record *Paludina*, *Cysclas*, and *Unio*, all fresh-water species, from the east slope of Residence Hill, Avery Island (29). No shells were found at the locality during the present survey (March 1935).

Vaughan (1925) and Howe and Moresi (1931, p. 98-99) record fresh-water and brackish species from the north slope of Jefferson Island (30). Although no fossils were found in this cut, the writer obtained two species of fresh-water mollusks from the depth of 110 feet from a well of the Jefferson Lake Oil Company (*Vivipara subpurpurea* Say and *Pleurocera acutum* Rafinesque) (31).

Since Jefferson Island and Avery Island are both salt domes of relatively recent uplift, these fossils have little significance. It is interesting, however, to note that *P. acutum* is not known living today nearer than Alexandria, Louisiana, on the Red River. The same species was found in the well at Baton Rouge (22).

Vermillion Parish: Hadley (Howe, Russell, and McGuirt, 1935, p. 14-15) lists shells from two cheniers in Vermillion Parish: (32) Chenier au Tigre and (33) Pecan Island. These are in all probability post-Pleistocene in age.

Jefferson Davis Parish: Shells were obtained from a seismograph crater in the center of SW ¼ SE¼ Sec. 15, T. 10 S, R. 5 W, 2¼ miles west and 4 miles south of

Welsh (34). The shells came from about sea level; the elevation of the land at this point is about 10 feet.

Shells were obtained from a borehole near Elton (35) on the west side of Bayou Nez Pique on the south side of Highway 190 between Kinder and Eunice, about 100 yards south of the highway and 50 yards west of the concrete foundation of an old saw mill. The hole was drilled in 1936 by David Cole of Oberlin, Louisiana, to the depth of 50 feet. The shell layer was about 1½ feet thick and occurred at a depth of 40 feet; the fauna was a mixture of brackish- and fresh-water species (*Rangia cuneata* Gray, *Campeloma subpurpurea*, Say, and *Elliptio* sp.). The elevation of the land at this point is about 32 feet; the shells therefore occur at about 8 feet. This locality is of special interest because it marks the highest elevation of the land at which Pleistocene marine or brackish fossils have been found along Atlantic or Gulf Coast between New York and Texas.

CAMERON PARISH: Previous collections from the shell ridge at Grand Chenier (36) have been listed by Maury (1920; 1922) and Hadley (Howe, Russell, and McGuirt, 1935, p. 14-15). The present writer has also made collections from the locality (Pl. 2, fig. 1).

A large collection of shells was obtained in September 1936 by the writer in the company of S. O. Burford of the Humble Oil and Refining Company from dredgings from the canal near Cameron Meadows Oil Field (37) (Pl. 2, fig. 2). The shells, all of which are known to be living in the Gulf today, are post-Pleistocene, probably roughly contemporaneous with those from Grand Chenier. The Cameron Meadows locality probably represents an old beach ridge that has undergone subsidence due to the building up of Cameron Marsh.

CALCASIEU PARISH: Shells have been obtained from shallow excavations up to elevation + 20 feet at several places in the vicinity of Lake Charles. The following have yielded fossils:

(38) Sewer excavations in Lake Charles.

(39) At Southern Pacific Railroad crossing of English Bayou, 6½ miles east of Lake Charles.

(40) Drainage ditches on Iowa Oil Field, Iowa, Louisiana.

(41) Boreholes near Vincent settlement.

(42) 3 miles south of Hecker on the south side of Irrigation Canal and 1.5 miles north of Bayou Serpent, and 2 miles east of Calcasieu River. (On line between Sections 16 and 17, T. 8 S, R. 7 W). The following section was noted:

	Feet
Soil and red clay	1
Oyster bed, clay matrix, slightly worn shells, some valves together	10
Concealed	2

DISCUSSION AND CONCLUSIONS

It seems probable that the lowest terrace of Florida—the Pamlico—with shore line at 25 feet, extends westward along the Gulf Coast into Alabama and Mississippi. It is possible, as suggested by Leverett (1931), that this terrace decreases in elevation westward toward the Mississippi River. Along the Gulf Coast of peninsular Florida marine fossils are known up to about 10 feet above sea level. However, along the western part of the State, fossils are very scarce and are known only from excavations or wells (Richards, 1938a, p. 1283-1284).

In Alabama, marine Pleistocene fossils are known only from wells (Fort Morgan), and up to about 3 feet above sea level (Mon Louis Island). The considerable depth to which Pleistocene fossils occur in the Fort Morgan wells may indicate a local sinking of the land. Thus the sediments brought down by the Alabama River and other tributaries of Mobile Bay may have caused a subsidence which is comparable on a smaller scale to the much greater subsidence produced by the sediments of the Mississippi River.

In Mississippi, the marine Pleistocene is recorded only from wells. The depth at which fossils are found increases greatly as one approaches the Mississippi River and in Terrebonne Parish, Louisiana, southwest of New Orleans, they are known from sea level down to at least —2470 feet.

The fossiliferous deposits extend up the Mississippi River but at decreasing depths (1200 feet at New Orleans). At Baton Rouge, a well yielded a mixture of brackish- and fresh-water species. North of Baton Rouge no marine Pleistocene fossils are known, but fresh-water mollusks have been found above the surface at several places (Richards, 1938b). Correlation of these localities is difficult because certain of the well records (as Baton Rouge) are from salt domes, so that the depth at which fossils were found is of little significance. Moreover, the deposits along the Mississippi River (Port Hudson), as was shown earlier in this report, probably represent a long period of time, including much of the Pleistocene as well as the Recent.

Fisk (1938b) refers the Fresh-water Pleistocene locality at Little Bayou Sara (23) to the Port Hickey terrace, which he regards as the youngest Pleistocene terrace in the region and which he correlates with the Peorian or mid-Wisconsin interglacial stage.

> "The zones of fossiliferous material accumulated in the coarser sediment during the initial stages of the ice retreat from the continent. During this time a rise in sea level caused by the melt waters from the glaciers was just beginning, the main streams were still entrenched, and the tributaries were carrying large quantities of coarse debris. The climate must have closely resembled that of the glacial stages and probably differed considerably from that of the latter part of interglacial time when conditions approached that of the present" (Fisk, 1938b, p. 24).

The fresh-water fossils from Little Bayou Sara and elsewhere confirm the indications of a cooler climate.

Considerable detailed field work will have to be done to show whether or not these fresh-water deposits (Port Hickey) may be correlated with the marine deposits along the Gulf Coast. If these latter deposits may be correlated with the Pamlico of Florida and the Atlantic Coast, as is here suggested, they were deposited at a time of high sea level during the last major interglacial stage. All the marine fossils are known to be living in the Gulf of Mexico today and therefore indicate a climate at

least as mild as the present, corroborating an interglacial dating. The Bayou Sara locality may represent an early part of the interglacial stage (Peorian?) when the climate was still cool, while at least some of the marine fossils of the coast represent a later warmer stage when sea level was higher.[4]

Pleistocene loess extends south along the Mississippi River into Louisiana, and fossils are known from Sicily Island, Catahoula Parish (Chawner, 1936, p. 137), and Tunica, West Feliciana Parish (Richards, 1938c, p. 47-57). These fossils are almost entirely land shells, and the loess is usually regarded as of aeolian origin. While the fossiliferous loess and the fresh-water Pleistocene deposits do not occur together at any place, certain fresh-water fossiliferous deposits are overlain by a loess-like material. The writer (Richards, 1938b, p. 28-31) discussed such localities at Little Bayou Sara, Louisiana, and Washington, Mississippi.

Marine Pleistocene fossils are found in wells in coastal Louisiana west of the Mississippi River, but they are found at depths decreasing with distance away from the Mississippi River. As Howe, Russell, and McGuirt (1935, p. 37) have pointed out,

> "It is only in the region of the lower Mississippi Delta, south of the line from New Iberia to Slidell that marine Pleistocene sediments are commonly found in wells."

In Calcasieu Parish, in the vicinity of Lake Charles, marine Pleistocene fossils are found up to an elevation of +20 feet. Howe, Russell, and McGuirt (1935, p. 37) have suggested that these fossils were deposited when sea level was actually lower than at present, and that as subsidence continued in the south a slow rise was taking place in the land to the north. However, the marine deposits of the Lake Charles region appear to be similar to and continuous with those of the Beaumont of Texas (Barton, 1930; Doering, 1935). The Beaumont is relatively horizontal from the Sabine River to the Mexican border and is thought to have been deposited during a higher stand of the sea (probably last major interglacial), just before the last low sea level.

It therefore seems preferable to the writer to regard the marine deposits near Lake Charles as having been deposited during a high stand of the sea, or at least when the sea was as high as it is today. The weight of the Mississippi sediments was not so great as far west as Lake Charles, a fact borne out by the finding of Pliocene fossils at relatively shallow

[4] The problem of the extent of the Peorian interglacial stage is somewhat controversial. Numerous workers have raised the question as to whether there was sufficient deglaciation during Peorian time to have appreciably raised the sea level. If this be true, interglacial deposits formed during a high stand of the sea referred to the Peorian should preferably be called Sangamon. On the other hand, the extent of the Iowan glacial stage is in doubt; this may have been a local ice advance causing little lowering of sea level, while the subsequent Peorian interglacial stage may have brought about a high stand of the sea similar to that of the Sangamon. However, this problem lies outside of the present discussion.

depths in Cameron and Vermillion parishes. The major sinking of the Mississippi Delta was probably largely limited to its present flood plain.

There appears to be good evidence along the East Coast as well as parts of the Gulf Coast of a marine Pleistocene formation deposited during a higher stand of the sea, and it seems best for the present to regard the Lake Charles beds as part of this deposit. A slight rise of the land in the Lake Charles area would not be out of harmony with the evidence from elsewhere along the coast.

The locality near Elton in Jefferson Davis Parish (35), Louisiana, occurring as it does at a higher elevation, may possibly represent a stage of the Pleistocene earlier than the Lake Charles localities. In this connection it is interesting to note that the Citronelle gravel, formerly regarded as of Pliocene age (Matson, 1916), is now regarded as of early Pleistocene age (Chawner, 1936, p. 134-137; Fisk, 1938a, p. 151-154). Fossil plants from the Citronelle were described by Berry (1916).

PLEISTOCENE MOLLUSKS FROM ALABAMA, MISSISSIPPI, AND LOUISIANA

The following list includes all Pleistocene marine mollusks reported on good authority from Alabama, Mississippi, and Louisiana. This includes material obtained by the present writer as well as that reported by previous workers. Whenever possible, the identifications of this latter material have been verified during the present investigation. Certain species of doubtful identification or which may be of either Pleistocene or Pliocene age are omitted from the list.

Since the land and fresh-water Pleistocene fauna of the region was discussed in previous reports (Richards, 1938b), they are not included in Table 4.

TABLE 4.—*Pleistocene marine mollusks*

PELECYPODA

	Alabama	Mississippi	Louisiana
Leda acuta Conrad	2*	5	11–15–16–20–24–25–26–36–37
Arca campechiensis Gmelin	2	.....	9–11–14–15–16–17–18–24–25–26–32–33–36–37
A. transversa Say	1–2–3	.....	9–13–14–15–16–17–18–19–20–24 25–26–27–33–37
A. ponderosa Say	2	5	9–11–13–17–18–25–26–33–36–37
A. incongrua Say	.....	.....	14–24–25–26–32–33–36–37
Glycymeris pectinatus Gmelin	.....	.....	15–26
Atrina serrata Sowerby	.....	.....	37
A. rigida Dillwyn	.....	.....	11–14
Ostrea virginica Gmelin	2–3	.....	9–14–15–16–24–25–26–32–34–36–37–38–41–42

* Numbers refer to localities. *See* Plate 3.

MAP OF ALABAMA, MISSISS
Showing fossil

MAP OF ALABAMA, MISSISSIP
Showing fossil loc

MISSISSIPPI, AND LOUISIANA

ing fossil localities

TABLE 4.—*Pleistocene marine mollusks—Continued*

PELECYPODA—CONTINUED

	Alabama	Mississippi	Louisiana
Plicatula gibbosa Lamarck	.....	.....	14–15
Pecten gibbus Linné	2–3	.....	14–24–25–26
Anomia simplex d'Orbigny	2	.....	9–14–15–17–19–26
Mytilus hamatus Say	3	.....	25–26–37
Modiolus demissus Dillwyn	1	.....	14–38
Congeria leucopheata Conrad	.....	.....	25–26
Pandora trilineata Say	.....	.....	11
Crassinella lunulata Conrad	2	.....	11–14–15–18–25–26–37–38–41
Crassatellites gibbsii Tuomey and Holmes	.....	.....	13
C. dalli Vanatta	.....	.....	15
Echinochama arcinella Linné	.....	.....	13–14
Diplodonta sp	1	.....	16–32–33
Phacoides floridanus Conrad (?)	.....	.....	17
P. radians Conrad	.....	.....	13–14
P. crenella Dall	1–2	.....	20–41
P. multilineatus Tuomey and Holmes	1–2	.....	15–16–18–24–25–26–27
P. amiantus Dall	2	.....	10–11–14–15–16–18–24–25–26
Lucina jamaicensis Lamarck (*L. pectinatus* Gmelin)	.....	.....	14
Divarcella quadrisulcata d'Orbigny	2	.....	
D. cf. *densata* Wood	1	.....	
Cardium robustum Solander	2–3	.....	9–11–15–24–25–26–36–37
C. isocardia Linné	.....	.....	14
C. muricatum Linné	.....	.....	11–14–37
C. serratum Linné	.....	.....	14–37
C. mortoni Conrad	.....	.....	11–37
Docinia discus Reeve	.....	.....	11–14–15–19–25–26–36–37
Macrocallista maculata Linné	2	.....	
Callocardia sayana Conrad	2	.....	
C. texasana Dall	.....	.....	25–26–36
Chione cancellata Linné	2	.....	11–14–15–24–25–26
C. intepurpurea Conrad	2	.....	11–13–14–15–25–26
C. latilirata Conrad	.....	.....	11–13–15–20–24
C. grus Holmes	.....	.....	14–15–16–25
Venus mercenaria Linné	3	.....	9–11–25–26–34–37–41
V. campechiensis Gmelin	2	.....	37–41
Anomalocardia cuneimeris Conrad	.....	.....	15
Gemma gemma Totten	2	.....	
Parastarte triquetra Conrad	2	.....	
Petricola pholadiformis Lamarck	.....	.....	14
Tellina tenera Say	2	.....	11–26
T. lintea Conrad	.....	.....	18
T. alternata Say	.....	.....	11–14–19–24–26–37
T. sayi Deshayes	.....	.....	11
Macoma tenta Say	.....	.....	11–15
M. constricta Bruguière	.....	.....	14–36–37
Tellidora cristata Recluz	.....	.....	11
Strigilla carnaria Linné	1	.....	
S. flexuosa Say	.....	.....	14–15–18–19
Arba aequalis Say	1–2	.....	14–15–18–19–25–36–37
Cumingia tellinoides Conrad	.....	.....	36
Semele bellastriata Conrad	.....	.....	14
S. nuculoides Conrad	.....	.....	15
S. proficua Pulteney	.....	.....	37
Donax variabilis Say	1–2	.....	11–37

TABLE 4.—*Pleistocene marine mollusks—Continued*

PELECYPODA—CONTINUED

	Alabama	Mississippi	Louisiana
D. tumidus Philippi	2		10–15–36
D. roemeri Philippi			37
Tegelus gibbus Spengler			37
T. divisus Spengler			14
Ensis directus Conrad			37
Mactra fragilis Gmelin			15
M. rimilis Say	2		14–36
Mulinia lateralis Say	1–2	5	10–15–16–17–18–19–20–25–26–36–37–38–41
M. lateralis corbuloides Deshayes			14–36
Rangia cuneata Gray	2		9–16–19–21–22–24–25–26–27–31–32–33–34–35–36–37
R. flexuosa Conrad			14–37
Labiosa canaliculata Say			14–25–26–37
Ervilia cf. *nitens* Montagu	1		
Corbula contracta Say			14–24–25–26–37
C. barrattiana Adams	2		16
C. disparilis d'Orbigny			26
Paramya subovata Conrad	1		
Pholas costata Linné			11–14–25–26–27–36–37
Martesia striata Linné (?)			14

GASTROPODA

Fissurella alternata Say			37
Neritina virginea Linné	3		
N. reclivata Say			26
Scalaria multistriata Say			24–25–26
S. lineata Say			25–36
S. sayana Dall			36
S. angulatum Say			37
Niso interrupta aeglees Bush			26
Pyramidella crenulata Holmes			11–18–19
Turbonilla interrupta Totten			11–25–26
Turbonilla sp			37
Natica pusila Say			11–15–26–27
Polinices duplicata Say	2–3		9–14–15–16–17–25–26–32–33–36–37
Sinum perspectivum Say			14
Crepidula fornicata Linné	2		11–13–14–19
C. plana Say			14–15–19–37
Truncatella bilabiata Pfeiffer			16
Adeorbis supranitidus Wood			25
Architectonica granulata Lamarck			14
Littorina irrorata Say			14–32–37
Turritella variegata Linné			24–25–26
Vermetus sp			24–26
Caecum pulchellum Stimpson			11
Modulus modulus Linné			11–19
Seila adamsii Lea			37
Cerithium sp	2		
Strombus pugilis alatus Gmelin			14–36
Cassis inflata Shaw			14–24–25
Pyrula papyratia Say			14
Distorsio clathrata Lamarck			14

TABLE 4.—*Pleistocene marine mollusks—Continued*

GASTROPODA—CONTINUED

	Alabama	Mississippi	Louisiana
Murex mesorius Sowerby			14
M. fulvescens Sowerby			24–26–36
M. pomum Gmelin			14
Urosalpinx cinerea Say			11
Eupleura caudata Say			11
Thais haemastoma floridana Conrad			14–18–26–32–36–37
Columbella lunata Say			11–25–26
C. avara Say	2		11–16–25–37
C. obesa Adams			25–26–36–37
Nassa vibex Say			9–14–18
N. acuta Say	1	5	11–15–16–18–19–24–25–26–27–37
Cantharus cancellaria Conrad			14–36–37
Fulgur perversum Linné			11–14–33–36–37
F. canaliculata Linné			(New Orleans)
F. pyrum Dillwyn			14–36
F. pyrum incile Say			36
F. carica Gmelin			36
Fasciolaria gigantea Kiener			14
F. distans Lamarck			14
Marginella sp.	2		32
Oliva sayana Ravenel (*O. litterata* Lamarck)	2		9–11–13–14–17–18–19–24–25–26–27
Olivella mutica Say	2		15–16–18–19–24–25–26
Terebra dislocata Say			11–14–18–19–24–25–26
T. concava Say			18
T. protexta Conrad			16–18
T. cinerea Born			14
Conus pealei Green	1		
Mangelia cerina Kurtz and Stimpson			11–24–25–26–37
M. cerinella Dall			26
M. limonitella Dall			26
M. rubella Kurtz and Stimpson			25
Cancellaria reticulata Linné			14
C. conradina Dall			13
Acteocina canaliculata Say			16–25–26–36–37
Cylichnella bidentata d'Orbigny			25
Melampus flavus Gmelin			37

SCAPHOPODA

Dentalium gouldii Dall			16
D. texasianum Philippi			11–25
D. acus Dall	1		20

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